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OPTIMIZATION AND SIMULATION OF JUST-IN-TIME SUPPLY PICKUP AND DELIVERY SYSTEMS

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ABSTRACT OF DISSERTATION

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A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Engineering
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By
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A just-in-time supply pickup and delivery system (JSS) manages the logistic operations between a manufacturing plant and its suppliers by controlling the sequence, timing, and frequency of container pickups and parts deliveries, thereby coordinating internal conveyance, external conveyance, and the operation of cross-docking facilities. The system is important to just-in-time production lines that maintain small inventories.

This research studies the logistics, supply chain, and production control of JSS. First, a new meta-heuristics approach (taboo search) is developed to solve a general frequency routing (GFR) problem that has been formulated in this dissertation with five types of constraints: flow, space, load, time, and heijunka. Also, a formulation for cross-dock routing (CDR) has been created and solved. Second, seven issues concerning the structure of JSS systems that employ the previously studied common frequency routing (CFR) problem (Chuah and Yingling, in press) are explored to understand their impacts on operational costs of the system. Finally, a discrete-event simulation model is developed to study JSS by looking at different types of variations in demand and studying their impacts on the stability of inventory levels in the system.

The results show that GFR routes at high frequencies do not have common frequencies in the solution. There are some common frequencies at medium frequencies and none at low frequency, where effectively the problem is simply a vehicle routing problem (VRP) with time windows. CDR is an extension of VRP-type problems that can be solved quickly with meta-heuristic approaches. GFR, CDR, and CFR are practical routing strategies for JSS with taboo search or other types of meta-heuristics as solvers. By comparing GFR and CFR solutions to the same problems, it is shown that the impacts of CFR restrictions on cost are minimal and in many cases so small as to make simplier CFR routes desirable.

The studies of JSS structural features on the operating costs of JSS systems under the assumption of CFR routes yielded interesting results. First, when suppliers are clustered, the routes become more efficient at mid-level, but not high or low, frequencies. Second, the cost increases with the number of suppliers. Third, negotiating broad time windows with suppliers is important for cost control in JSS systems. Fourth, an increase or decrease in production volumes uniformly shifts the solutions' cost versus frequency curve. Fifth, increased vehicle capacity is important in reducing costs at low and medium frequencies but far less important at high frequencies. Lastly, load distributions among the suppliers are not important determinants of transportation costs as long as the average loads remain the same.

Finally, a one-supplier, one-part-source simulation model shows that the system's inventory level tends to be sticky to the reordering level. JSS is very stable, but it requires reliable transportation to perform well. The impact to changes in kanban levels (e.g., as might occur between route planning intervals when production rates are adjusted) is relatively long term with dynamic after-effects on inventory levels that take a long time to dissapate. A gradual change in kanban levels may be introduced, prior to the changeover, to counter this effect.

KEYWORDS: Just-in-time Systems, Vehicle Routing Problems, Meta-heuristics, Pull Productions, Discrete Event Simulations

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To

Leeyin, Ah Sheng, Ah Yin, Ah Yen, and Ah Wen

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Chapter One: Introduction

1.1 Overview

A just-in-time supply pickup and delivery system (JSS) manages the logistic operations between a manufacturing plant and its suppliers. The system controls the sequence, timing, and frequency of container pickups from the suppliers and subsequent parts deliveries to points-of-use at the just-in-time (JIT) plant. Formally, in the language of math programming, JSS may be viewed as a vehicle routing problem (VRP) with a number of extra requirements and special constraints. In practice, the system is divided into two major components due to complexity: internal conveyance – the handling of parts from trailers that have arrived at the plant and parked in the yard to the point of consumption on the line - and external conveyance – the handling of parts by trucks and trailers from the docks of suppliers to the yard at the plant. A JIT production line that relies on this system will receive its parts and raw materials regularly, frequently, and in small quantity. Using JSS, the production line can streamline the incoming workflow in the way ideal for continuous flow production. In fact, mature JIT and JSS systems are highly coupled and efficient, and require less internal material handling, less procurement and receiving paperwork, less storage space requirements, lower average inventory levels, shorter production and order lead times, while supporting operations management strategies that immediately detect and respond to operating problems.

The objective of JSS is to minimize transportation costs while making frequent deliveries of parts in small quantities. Frequent deliveries that rely on less-than-truck-load (LTL) shipments would yield a high transportation cost. Therefore, a consolidation of these small shipments into full truckloads involves scheduling pickup routes that visit many suppliers collectively. Such routes are frequently referred to as milkruns.

To schedule the pickups and deliveries, JSS first makes a forecast of the parts quantities required to meet the total vehicles order (TVO) to establish an estimated production rate over a short production planning interval (e.g., 4 weeks). The planning interval length depends on the both the volatility of demand and the ability of the system to adjust to changes in production rate. This ability depends on the engineering effort required to redesign both production lines (principally rebalancing) and supply logistics systems (principally re-routing and adjustment of pull parameters). From this production rate, a bill of materials expansion is performed to determine the parts needs, the suppliers, and the approximate pickup volumes at each supplier. Then, a supplier database and mapping software are used to convert the relevant information into the appropriate parameters for the routing process. Throughout the routing process, JSS considers many factors including the plant production, the supplier's docking schedule and capacity, the transit distances and times, the need for contingencies in the event of unpredictable factors such as weather conditions, and the number of trailers necessary to run the system.

Due to the complex nature of routing problems, it is always easier to design many small problems than fewer large ones and hence the external conveyance routing problem mentioned above is broken into sub problems. To break down the problem, attributes, such as geographic region, travel distances, and part types, are used to separate the system into smaller route design problems. The separation method is a divide-and-conquer strategy, which simplifies the problem for the subsequent optimization process. The price of breaking down the problem is hard to determine, as it is a question about trading global optimality for fast solutions. It also highly depends on the efficiency of the routing procedure. Simply stated, we want the problems to be small enough so that the routing procedure can handle them, but large enough so that the overall solution is close to the true optimum point.

For the external conveyance, the solution of JSS is a JSS schedule. It consists of many mapped routes that travel round-trip between the plant and the suppliers. Generally, a route serves several suppliers in a local region to reduce the transportation cost. A number of trucks and trailers are assigned on each route to transport the shipments. Each trailer departs from the plant with empty pallets and a kanban order authorizing the supplier to fill those pallets with new parts that will be picked up at a particular later visit to the supplier depending on the supplier's manufacturing lead time. (The kanban order itself may have been transmitted earlier to the supplier through electronic means, decreasing the lead time to respond to the replenishment signal relative to physical transport of the kanban cards.) Upon arrival at a supplier, workers replace these empty pallets with due shipments from an earlier kanban order and the trailer proceeds to the next supplier. After visiting the last supplier on the route, the trailer returns to the plant, completing the route. To prevent an inventory buildup, JSS typically schedules each supplier to be visitied many times each day. Often this is accomplished by running a given route multiple times a day. Each run counts as one pickup for a given part source located at a supplier.

Generally, parts are shipped in containers and containers are bundled in pallets. Associated with each pallet is the identity of the "part sources" and the "consumption points" or, respectively, the origins of the part at the suppliers and the destinations of the part at the plant. A given supplier may serve as multiple part sources, and a part source may serve multiple consumption points. A given consumption point, on the other hand, is always associated with one part source. A pallet with multiple consumption points is called a mixed pallet or a cross-docking pallet (Hauser, 2002). (Note that a cross-docking pallet and an external cross docking facility are not related.) Each part source and consumption point has a dock assigned at the plant for loading and unloading.

JSS do not control the parts ordering; instead, each part container has a supplier kanban attached to it. Orders are placed right after a container is open for use by sending the card physically or electronically to the supplier as a replenishment signal and hence are based on actual production rates. During production, there are a fixed number of kanban cards in circulation between the plant and the suppliers controlling WIP levels. Production rates, transportation lead times, manufacturing lead times, pickup frequency and the part counts per pallet determine the required number of cards. The kanban system is an independent system working on top of JSS. It thinks of JSS as essentially a conveyer, stretching from the supplier to point-of-use. Nevertheless, JSS decisions can adversely affect the kanban flow, especially the lead-time for parts, by simply diverting the flow of parts from one route to another. Moreover, production pace, leveling of order launch, and avoidance of production disruptions are necessary for smooth conveyance of parts using the kanban system while avoiding the need for large excess transportation capacity or excess inventory.

JSS allows the use of cross-docking facilities. A cross docking facility is a warehouse without the long-term capacity to store parts. It is a consolidation point to serve the pickup from a local region of suppliers. Its functions include sorting the incoming pallets and preparing the outgoing trailers. With the introduction of cross-docking facilities to JSS, the routes that are involved separate into main routes and sub routes. The main routes run between the plant, the cross docking facility, and the direct suppliers. The sub routes are dedicated to serving a cross docking facility and its cross dock suppliers. A cross dock may serve multiple manufacturing plants.

For the internal conveyance, JSS establishes a docking sequence that organizes all the loading and unloading of trailers for the plant. After a trailer returns to the plant, it waits for docking in a designated parking lot. When the plant is ready, the trailer will dock at various docks as determined by its contents or the consumption points of the parts in the trailer. At each dock, a number of fork lifts remove the appropriate pallets to the floor staging area, the sequence area, and the lane storage area, based on the types of pallets. They then fill the trailer with the appropriate amount of empty pallets, according to the new kanban order and the new trailer diagram. JSS designs a trailer loading diagram for each route to allow efficient loading and unloading of many different parts from various suppliers at the docks. After completing all the docking sequences, the trailer returns to the parking lot, prepared for another round of pickups. A trailer itself does not run a particular frequency or pickup number. A route schedule can operate a smaller number of trailers than that route's pickup frequency, to establish a given trailer's rotation.

1.2 Literature Review

This section reviews the existing JIT literature related to JSS. The review is divided into supply chain management, inventory models, and JIT purchasing.

1.2.1 Supply Chain Management and JSS

In a review paper, supply chain management (SCM) is described as an increasing prevalent approach to purchasing and distributing goods from the suppliers to the manufacturers, wholesalers, and retailers, where the process has been increasingly integrated and electronically handled, replacing inventory with information, and planning for the long term success of a buyer-seller relationship (Tan, 2001). From this perspective, JSS is not all but one part of of larger system that stretches from raw material extractors to the final consumers. Despite the larger view, supply chains are so complex that no one organization can directly control them and there are many pitfalls that companies should be aware (Lee and Billington, 1992). The effort over the last decade is in integrating a buyer's immediate supplier into the internal production, management, and logistics, resulting in a better flow of goods (Houlihan, 1987). For some reasons, JSS as it has been applied at Toyota seems to have been on the right track of this development in the more general field of supply chain management.

Lean manufacturing has long stressed the importance of establishing good manufacturer-supplier relationship. The belief is echoed in the supply chain literature that a smooth flow of materials between the suppliers and buyers is one of the key elements needed for a continuous flow process (Schonberger, 1984). In addition, supplier involvement in product design allows unexpected cost savings that take advantage of the supplier's capability and technology. Toyota went further ahead with their Toyota Suppliers Support Center, which develops and improves the supplier's capability and technology in the area around their manufacturing plants. Despite that, a study shows that although the buyer benefits greatly from this relationship, the suppliers do not unless they too adopt the lean manufacturing techniques (Dong et al., 2001) and work with OEMs that follow the philosophy of supplier relations espoused by the lean philosophy.

1.2.2 Inventory models and JSS

There are a number of studies in inventory management and supply reordering that considers JIT inbound logistics. The papers presented here differ from conventional inventory models (Bramel and Simchi-Levi, 1997), such as economic order quantity (EOQ) and its stochastic versions, in the sense that these models incorporate JIT considerations and often identify with the needs for lean production. In fact, Schniederjans and Cao (2000) shows that the EOQ, which drives for larger batch sizes in the name of economies of scale, is presented in an overly favorable light when compared to JIT ordering because it does not consider the space savings created in the JIT system. Moreover, the paper does not look into other advantages of JIT logistics such as improved quality control, rapid detection and response to problems, and maintaining a healthy stress to permanently eliminate problems, as presented by Chuah and Yingling (2001). These cited economic benefits represent avoidance costs that are large intangible but believed to be highly significant in magnitude.

A study of a single-buyer, single-supplier inventory model to create frequent deliveries and small lot sizes shows that frequent deliveries is better than single-delivery policy, resulting in cost savings (Kim and Ha, 2003). They also conclude that optimal delivery size converges as the number of deliveries and the total order quantity increase, demonstrating the stability of the system. Another paper incorporate transportation costs into inventory models for a JIT inbound logistics system using the freight rates (Swenseth and Godfrey 2002). They, however, do not consider the actual routing process. In another paper, Zhuang studies a JIT delivery model from a batch production supplier's perspective and cites that the selling price of goods can affect delivery quantity and delivery frequency (Zhuang, 1994). It is a numerical model that adjusts the selling price to maximize profits for both the buyer and the supplier.

1.2.3 JIT purchasing

JIT purchasing describes management's decision to maintain a smaller inventory by regularly purchasing goods in smaller lot size. JIT purchasing is related to JSS since JSS directly supports the kanban system, which executes purchases for replenishment. In addition, decision making in selecting suppliers affects JSS routing. Vonderembse et al. remarks that the product cost is not the only criterion for a supplier to compete in JIT purchasing. Other factors include product quality, performance, delivery reliability, and availability (Vonderembse et al., 1995). The paper also indicates that suppliers are willing to accept longer contracts and are getting involved in product development. Gunasekaran (1999) presents a review of JIT purchasing and mentions the trend for manufacturers to integrate purchasing with design, production, marketing, distribution, and accounting through concurrent engineering.

To establish closer cooperation, Pragman notes that many suppliers send a full-time JIT purchasing representative to work with the manufacturers (Pragman, 1996). At the Toyota automotive plant in Georgetown, Kentucky (TMMK), Toyota not only manages the entire inbound logistics, but also invites several experts from their logistics partner to work with them full-time in their office. It demonstrates the go-and-see method (Genchi genbutsu), i.e. one of the important principles in a Toyota's partnership with Transportgistics (Minyon, 2003). In a presentation about Genchi genbutsu, Tanigawa explains that things are simple when it is handled first hand, but become very complex after it has been processed through spreadsheets and charts (Tanigawa, 2003).

1.3 Research Purpose and Scope

The overall goal of this research is to develop a better understanding of JSS and to make contributions to improve the system. This research studies four major aspects of the JSS and its embedded vehicle routing problem.

First, in optimization-based route design, a new general frequency routing formulation (GFR) is developed for the system and a meta-heuristics approach for solving that formulation is established. General frequency routing is a mathematical formulation that can satisfy all features of JSS. It is a difficult optimization problem with five types of constraints: flow, space, load, time, and heijunka. Our solution approach applies features of taboo search in combination with other search strategies under a unified metaheursitics framework.

Second, this research also studies cross-dock routing (CDR) problems. Cross-docking facilities are part of the JSS system whereby the system consolidates the shipments from the suppliers at some strategic locations, while extending their service time windows beyond the normal business hours. The formulation for CDR is created to handle the routing of these facilities. Taboo search is implemented to solve this problem.

Third, characteristics of common frequency routing problem (CFR) as developed by Chauh and Yingling (in press) are explored to understand their impacts on the costs of external conveyance. (Note that common frequency routing restricts all pickups on the same route to one frequency, constraining the search space in optimization-based route design. Hence, it is simpler than general frequency routing and easier to study, but would tend to result in higher cost solutions than GFR.) We study the effects of supplier clustering, production demand variation, vehicle capacity, and load distributions on the cost of operating a JSS under the CFR discipline. It is believed that similar relationships would also hold under GFR.

Finally, a discrete event simulation model is developed to study JSS. The connections between JSS and manufacturing system under real time operations are studied. This study identifies interesting inventory dynamics and identifies factors that contribute to this behavior.

1.4 Statements of Hypothesis

This dissertation addresses the following theses:

1. GFR can be solved with heuristics under reasonable computational time.
2. GFR routes when solved are more efficient, but not well organized.
3. GFR and CFR are practical routing strategies for JSS.
4. CDR is an extension of VRP type problems that can be solved quickly.
5. The impacts of CFR restrictions are minimal.
6. Concerning inventory dynamics in a JSS, long kanban lead-time is not desirable under an unstable system, although its effects are small under a stable system.

1.5 Some Important Definitions

For consistency and clarity, the following are the default meanings of the words when used in this thesis:

1. A *route* is a fixed order of visits to a set of suppliers to pickup a set of pallets (and to delivery their respective empty pallets) from an origin that is either the manufacturing plant or a cross docking facility.
2. A *schedule* is an ordered set of routes specifying the trailers, pickup frequencies, and run times of these routes.
3. A *docking sequence* is the order a trailer visits the various docks located within the plant.

1.6 Structure of the Dissertation

The following describes the organization of the dissertation contents:

Chapter 1: This chapter introduces the background of the system (JSS) that we addressed in our models formulations and our research studies using these models. It also defines the scopes and goals of the research.

Chapter 2: This chapter discusses the optimization-based formulations, GFR, CFR, and CDR, and presents the methods of solving them. A discussion of the solutions and their implications follows each section.

Chapter 3: This chapter studies the costs of JSS as a function of a major system design features such as supplier clustering and supplier demand variation. It assumes routing is done using the optimization-based CFR approach.

Chapter 4: This chapter presents the simulation studies of inventory dynamics in JSS systems.

Chapter 5: This chapter summarizes the contributions, the limitations, and the future directions of this research.

Appendix A: This appendix shows an A3 of this dissertation. (An A3 is a one page summary document used in lean manufacturing for succinct and effective communication of complex issues.)

Appendix B: This appendix discusses the meta-heuristics approaches, which includes a description of scatter search, taboo search, and ant colony optimization used in chapter 2. It presents the detailed implementation of these algorithms and compares their effectiveness to a VRPTW benchmark.

Appendix C: This appendix contains the input files and the input parameters for a number of problems referenced in the dissertation.

Appendix D: This appendix contains the simulation results of chapter 4.

Chapter Two: Optimization Approach to Route Design for a Just-in-Time Supply Pickup and Delivery System

A large part of a just-in-time supply pickup and delivery system (JSS) is routing. Routing may be formulated and solved as an optimization process, and a problem specifically tailored for JSS was first accomplished by Chuah and Yingling (in press). Such a problem looks simple when it is small, but becomes very complex as soon as the number of parts and suppliers increases. The goal of routing is to provide efficient transportation routes between the suppliers and the plant. Routing is presented as math programming problems that consider a variety of requirements expressed as constraints on the system. These constraints describe the roles of JSS in supporting the manufacturing plant and the suppliers' production systems. It is noted that in practice that JSS routing is done manually with computer assistance and is very time consuming. Indeed, the routing process is a bottleneck in the re-planning process for JIT systems to accommodate demand changes over time. Optimization shows promise for automating and speeding this process and may someday open the door for more frequent re-planning as well as day-to-day modifications of routes as unplanned events transpire.

2.1 General Frequency Routing Problem

General frequency routing problem (GFR) is a mathematical formulation developed in this dissertation that is designed to determine JSS routes described in the previous chapter. GFR may be viewed as an extension of the vehicle routing problem (VRP), VRP with time windows (VRPTW), and common frequency routing (CFR), a class of problems whose objective is to minimize the cost of delivery between a depot and a number of suppliers in a series of round trip routes.

A detailed review of VRP can be found in Bramel and Simchi-Levi (1997).

VRPTW is VRP with time windows constraints, where every supplier in VRPTW has an opening and a closing service hour that restrict routing to that window. In contrast to VRP, VRPTW requires temporal as well as spatial representation of the problem, dramatically increasing dimensionality. The problem is first discussed in Solomon (1986) and there are many ways to solve it (e.g., J. F. Bard et al., 2002; Desrochers et al., 1992; Taillard and Badeau, 1997). A feasible solution of VRPTW is also a feasible solution of VRP, since they have the same objective function.

Common frequency routing problem (CFR) is a vehicle routing problem that builds upon VRPTW to meet the needs of JSS (Chuah and Yingling, in press). CFR is restricted in the sense that it permits only one route to visit a part source, instead of multiple routes, but such routes have an optimized pickup frequency that performs multiple pickups. Although in reality JSS routes do not have this limitation, simplifying the route designs this way has many advantages both from the point of view of practical solution of the routing problem using optimization methods as well as execution and management of the routes in practice (See chapter 3). It is important to note that CFR employs a system-level space (or, effectively, total inventory) constraint that forces the routes to carry fewer parts in higher variety, such that every route needs several rounds of pickups each time period to ship their respective parts and keep pace with demand. Such multiple pickups reduce the shipment size while increasing the pickup frequencies.

The GFR problem presented below has the load constraints of VRP, the time windows constraints of VRPTW, and the pickup frequency and space constraint of CFR. Furthermore, all part sources in GFR have their own pickup frequencies, which are independent of the routes' pickup frequencies. In contrast to CFR, which requires each part source be served by a single route run at a determined frequency, a GFR schedule can use multiple routes to cover a set of part sources, while each route may only visit a partial set of these part sources. A solution to GFR consists of a number of these schedules that together cover all the part sources. This relaxation greatly expands problem dimensionality in order to more fully explore candidate route designs that might be deployed in practice. Note that a CFR solution can be converted to a GFR solution, but CFR cannot generate all the feasible solutions in GFR. The differences between the two problems will be clear after we compare their respective mathematical formulations in Section 2.1.2.

2.1.1 Literature Review

CFR is a unique problem with only a number of related papers (Chuah, 2000). The review below summarizes the literatures for GFR.

Concerning prior work that directly addresses JIT logistics, Popken devises an approach to consolidate inbound freight for JIT systems through transshipment points (Popken, 1994). He models the inventory costs of freights based on weights and volumes and considers tradeoffs in transportation and inventory holding costs, but his algorithm is intended for long term planning and does not directly consider vehicle routing.

Crainic and Rousseau develop a multi-commodity, multimode freight transportation algorithmic framework that includes frequency and vehicle routing (Crainic and Rousseau, 1986). The frequency is measured in terms of quality of service for each mode of transportation, instead of its effect on pickup loads. Although the paper does not concern JIT, it may be applied to the GFR problem by adding heijunka and space constraints.

Inventory Routing Problem (IRP) (Bard et al, 1998; Chien et al, 1989) combines the inventory system with the vehicle routing problem and usually deals with the distribution of goods rather than pickup of goods. IRP assumes that each supplier maintains a number of pallets and receives a delivery from a central depot when the number of pallets at that supplier is low. The IRP treatment of the problem differs from the kanban system for inventory control in JIT routing. The kanban system emphasizes a smooth flow of parts, instead of a complete reduction in total cost. Parts are preferably transported directly to the consumption points when they arrive at the plant without going through a warehouse.

In split delivery vehicle routing (SDVR), the suppliers' pickup loads may be split into different routes to save the distance cost. Dror and Trudeau analyze SDVR and present a local search heuristic on the problem (Dror and Trudeau, 1990). Mohri et al. suggested a mathematical programming based approach to the problem (Mohri et al, 1996). Fizzell and Giffin extend SDVR to consider time windows and present three heuristics to solve the extended problem (Frizzell and Giffin, 1995). The problem in this paper addresses SDVR in a different way, where arbitrary splitting of loads is not allowed unless the splitting is by frequency. It performs actual splitting of loads based on volume where a split of loads may, in certain cases, increase or decrease the total shipment volumes due to rounding. If a load from a supplier is going to several different consumption points in the plant, the load may split among multiple routes based on these consumption points.

There are two general approaches to solve VRP type problems: exact methods and heuristics. The exact methods are direct solving with linear programming (J. F. Bard et al., 2002) and column generation with Dantzig-Wolfe decomposition (Desrochers et al., 1992). Both methods employs branch and bound techniques to achieve integer solutions. In this research, we focused on the meta-heuristic approach as a practical approach for solving realistic size problems. Before jumping into that, we first discuss the mathematical formulation for GFR in the next section.

2.1.2 Mathematical Formulation

GFR, as formulated in this dissertation, is a mixed-integer non-linear optimization problem. Although the objective function is linear, some of the constraints are not linear. The objective function and the constraints are expressed in terms of variables, parameters, and inequalities. The objective of GFR is to minimize the sum of the transportation cost and the transport space/inventory cost. The transportation cost is proportional to the sum of all travel distances between the suppliers. The transport space cost is proportional to the sum of the average load per pickup for each transported part.

There are five types of constraints: flow, space, load, time, and heijunka. The flow constraints are similar to the flow constraints in VRP problem, except for the addition of the supplier (part source) pickup frequency. As such they insure continuity of the route through a given supplier and that the route starts and ends at the appropriate location. The space constraints define the transport space allocated to the various suppliers on the route. It is similar to the space constraint in CFR. The load constraints define the accumulation of load during the course of picking up parts at the suppliers. They also define the vehicle capacity constraint. The time constraints are constraints similar to those in VRPTW problem, where trailer can only visit the suppliers during their respective service hours. The heijunka constraint controls the supplier pickup volume by restricting the visiting time. Good heijunka means that pickups occur frequently and are evenly spaced over time; bad heijunka means otherwise. Heijunka is a Japanese word that means make things level and standard. It is a very important concept in this problem because it can reduce overall inventory needs and enable the enhanced operations control that results from continuous flow of parts through the supply chain in a JIT environment.

Figure 2.1 below shows the complete GFR formulation. Parameter definitions are given in Table 2.1 and variable definitions are given in Table 2.2. A detailed explanation follows.

Objective function :

$$\min \sum_i \sum_j \sum_k c_{ij}^k x_{ij}^k + \sum_i \sum_k \beta_i D_i^k$$

Bounds on variables:

$$x_{ij}^k = \{0,1\}$$
$$T_i^k \geq 0$$
$$L_i^k \geq 0$$
$$D_i^k \geq 0$$
$$s_i \geq 0$$
$$r_i \geq 0$$

flow:

$$r_i \sum_j \sum_k x_{ij}^k = 1 \quad \forall i$$
$$\sum_j \sum_k x_{ij}^k \geq 1 \quad \forall i$$
$$\sum_i x_{ij}^k - \sum_i x_{ji}^k = 0 \quad \forall j, \forall k$$
$$\sum_i x_{io}^k = 1 \quad \forall k$$
$$\sum_i x_{oi}^k = 1 \quad \forall k$$

space:

$$\sum_j D_i^k x_{ij}^k - r_i D_i \geq 0 \quad \forall i, \forall k$$
$$\sum_i r_i D_i \leq \gamma$$

time:

$$a_i \leq T_i^k \leq b_i \quad \forall i, \forall k$$
$$x_{ij}^k (T_i^k + t_{ij} - T_j^k) \leq 0 \quad \forall i, \forall j, \forall k$$

loads:

$$D_i^k \leq L_i^k \leq Q^k \quad \forall i, \forall k$$
$$x_{ij}^k (L_i^k + D_j^k - L_j^k) \leq 0 \quad \forall i, \forall j, \forall k$$

heijunka:

$$(b_i - a_i) r_i - s_i = 0 \quad \forall i$$
$$\sum_j x_{ij}^k x_{ij}^l \tau(s_i) \leq \left| T_i^k - T_i^l \right| \quad \forall i, \forall k, \forall l$$

Figure 2.1: The general frequency routing problem mathematical formulation

The formulation corresponds to a graph with nodes and edges. Each node in the graph is a part source. A special node is designated as the origin or the manufacturing plant. A route starts and ends with this node. There are edges connecting every node to every other node in the graph. Associated with each edge is a cost proportional to the travel distance between two nodes.

The formulation uses three indices: *i, j,* and *k*. Both index *i* and index *j* refers to a node in the graph, i.e. a particular part source. For an example, the count of all *i* is the number of nodes in the formulation. Both i and j are necessary because a pair of indices are required to express a connection between a pair of nodes. When i or j equals the special value o, we are referring to the origin of the graph, the manufacturing plant. Index k, on the other hand, refers to a route. A count of all k is the possible number of routes in the solutions. Candidate routes are generated in the course of a solution to the problem and need not be enumerated a priori.

Parameters are constant values set prior to optimization. The parameters of GFR are listed in Table 2.1 below:

Table 2.1: The parameters of general frequency routing problem

Symbols	Descriptions
a_i	The start of service time of node i.
b_i	The end of service time of node i.
c_{ij}^k	The cost of traveling, usually proportional to the distance, between nodes i and j on route k.
t_{ij}	The travel time between nodes i and j.
D_i	The quantity of load to pickup at or deliver to node i per unit time period.
Q^k	The transportation capacity limit of a route, normally due to the size of a trailer.
β_i	The coefficients for the space or inventory cost (of node i) in the objective function.
γ	The amount of space, or effectively, inventory, allocated to the entire system.

Variables represent degrees of freedom in the solution space and their values describe a solution. The variables of GFR are listed below:

Table 2.2: The variables of general frequency routing problem

Symbols	Descriptions
x^k_{ij}	A binary equal to one if node *i* connects to node *j* in route *k* and zero otherwise. The x^k_{ij} define the routes by identifying the connections *i, j* that the route follows.
T^k_i	The time when route *k* reaches node *i*.
L^k_i	The cumulative space reserved for the load when the vehicle traversing route *k* arrives at node *i*.
D^k_i	The load to pickup at or deliver to node *i* when route *k* arrives.
s_i	The loading and unloading time at node *i*.
r_i	The interval between pickups or deliveries at node *i* or, equivalently, the inverse of frequency that node *i* is visited.

As mentioned earlier, there are five types of constraints. Each type of constraint is a set of inequalities that defines the solution space of the problem. These inequalities and their detailed descriptions are given below:

Table 2.3: The inequalities of general frequency routing problem

Inequalities	Descriptions
$r_i \sum_j \sum_k x^k_{ij} = 1 \quad \forall i$	The interval between pickups (proportion of the unit time period) is the inverse of the number of pickups during the unit time period.
$\sum_j \sum_k x^k_{ij} \geq 1 \quad \forall i$	At least one route leaves part source *i*.

Table 2.3 (continued)

$\sum_i x_{ij}^k - \sum_i x_{ji}^k = 0 \quad \forall j, \forall k$	In every route, the number of arrivals and the number of departures at a part source are equal, insuring continuity of the routes.
$\sum_i x_{io}^k = 1 \quad \forall k$	All routes *k* return to the origin or the plant.
$\sum_i x_{oi}^k = 1 \quad \forall k$	All routes *k* leave the origin or the plant.
$\sum_j D_i^k x_{ij}^k - r_i D_i \geq 0 \quad \forall i, \forall k$	The load to pickup for part source *i* on route *k* is greater than or equal to the load required to meet demand for part *i*, $r_i D_i$.
$\sum_i r_i D_i \leq \gamma$	The sum of all loads per pickup uses at most the space allocated for the entire operation, γ. Note that as γ decreases, routes must be run at higher frequency to insure that storage space or inventory at the plant does not exceed γ in aggregate.
$a_i \leq T_i^k \leq b_i \quad \forall i, \forall k$	A route *k* visits a part source *i* during its open service time given by $[a_i, b_i]$
$x_{ij}^k (T_i^k + t_{ij} - T_j^k) \leq 0 \quad \forall i, \forall j, \forall k$	If there is a travel between a pair of nodes *i* and *j* by route *k* ($x_{ij}^k = 1$), the difference in time between the arrival at the next node and the departure at the previous node is at least the traveling time, t_{ij}.
$D_i^k \leq L_i^k \leq Q^k \quad \forall i, \forall k$	The space allocated on the trailer prior to the visit of part source *i* on route *k* is at least the load it picks up at part source i, D_i^k and at most the capacity of the trailer running the route, Q^k.

Table 2.3 (continued)

$x_{ij}^k(L_i^k + D_j^k - L_j^k) \leq 0 \quad \forall i, \forall j, \forall k$	If there is a travel between a pair of nodes ($x_{ij}^k=1$), the difference in aggregate space allocated between the current part source and the previous part source is the load picked up at the current node, D_j^k.
$(b_i - a_i)r_i - s_i = 0 \quad \forall i$	The fraction of the time window allocated per pickup, $(b_i-a_i)r_i$ must be equal to the time required to unload and load the trailer, s_i.
$\sum_j x_{ij}^k x_{ij}^l \tau(s_i) \leq \left\| T_i^k - T_i^l \right\| \quad \forall i, \forall k, \forall l$	The time between visits to a node is greater than or equal to a function $\tau_i()$ of the loading and unloading time, s_i.

For sake of comparison, below is the CFR mathematical formulation as presented in Chuah and Yingling (in press):

Objective function : $\quad min \sum_i \sum_j \sum_k f^k c_{ij} x_{ij}^k + \sum_i \sum_j \sum_k \beta_i D_i^k x_{ij}^k$

variables:

$x_{ij}^k = \{0,1\}$

$T_i^k \geq 0$

$L_i^k \geq 0$

$f^k \geq 0$

flow:

$\sum_j \sum_k x_{ij}^k \geq 1 \quad \forall i$

$\sum_i x_{ij}^k - \sum_i x_{ji}^k = 0 \quad \forall j, \forall k$

$\sum_i x_{io}^k = 1 \quad \forall k$

$\sum_i x_{oi}^k = 1 \quad \forall k$

space:

$\sum_i \sum_j \sum_k D_i^k x_{ij}^k \leq \gamma$

time:

$a_i \leq T_i^k \leq b_i - \tau(f^k) \quad \forall i, \forall k$

$x_{ij}^k(T_i^k + t_{ij} - T_j^k) \leq 0 \quad \forall i, \forall j, \forall k$

loads:

$D_i^k \leq L_i^k \leq Q^k \quad \forall i, \forall k$

$x_{ij}^k(L_i^k + D_j^k - L_j^k) \leq 0 \quad \forall i, \forall j, \forall k$

Figure 2.2: The common frequency routing problem mathematical formulation

The definitions of variables and parameters in CFR are identical to GFR. CFR, however, employs a parameter, f^k, not employed in GFR, where f^k is the pre-assigned frequency of route k, which may or may not be selected by the solution (multiple choices are available). Moreover, the quantity of parts picked up by route k is D_i^k as determined by dividing the total demand per time unit by the number of pickups per time unit and applying a rounding factor.

2.1.3 Differences in the Utilization of Time Windows between GFR and CFR

In CFR, there is no inequality constraint for heijunka, as it is assumed that the f^k routes in CFR are equally spaced over the maximum possible span of the time windows visited on the route. This span or time band for distributing the routes depends on (i) the time windows of each part source, (ii) the sequence the part sources are visited, and (iii) the transit times between part sources, see Figure 2.3. Nevertheless, the assumption potentially limits each route in the solution to a narrow band of time, wasting a large portion of the suppliers' time windows. This effect is most pronounced when one visits a supplier that with a late opening time window and later in the route visits a supplier with an early closing time window after a long transit time between these suppliers. Although not permitted in CFR, dropping a number of pickups from a limiting supplier can widen the band.

The band of time window also exists in GFR, albeit a little bit different, as there are different heijunka requirements in GFR. GFR allows sharing of part sources and splitting of the part source load, where two or routes can serve the same node in the graph. Therefore, the band as discussed above is wider in GFR. In fact, routes in GFR may crisscross a supplier time window to avoid the limited time, as shown in Figure 2.4. Crisscrossing, or out of order suppliers visiting, is one of the reasons some solutions in GFR are not feasible in CFR.

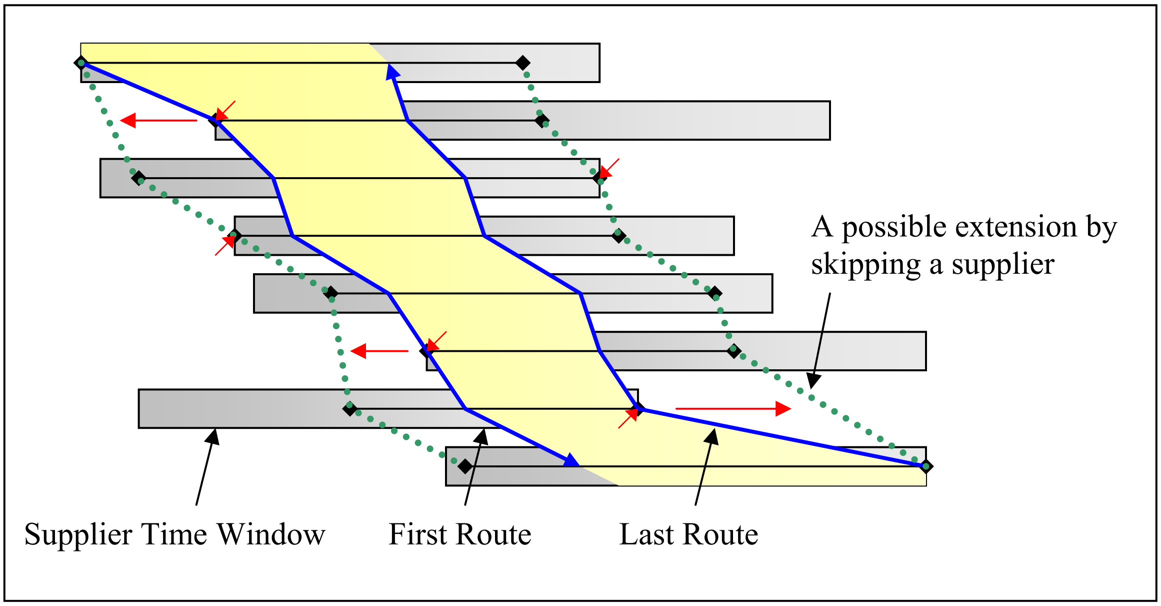


Figure 2.3: A limited band of time window is formed from a CFR solution

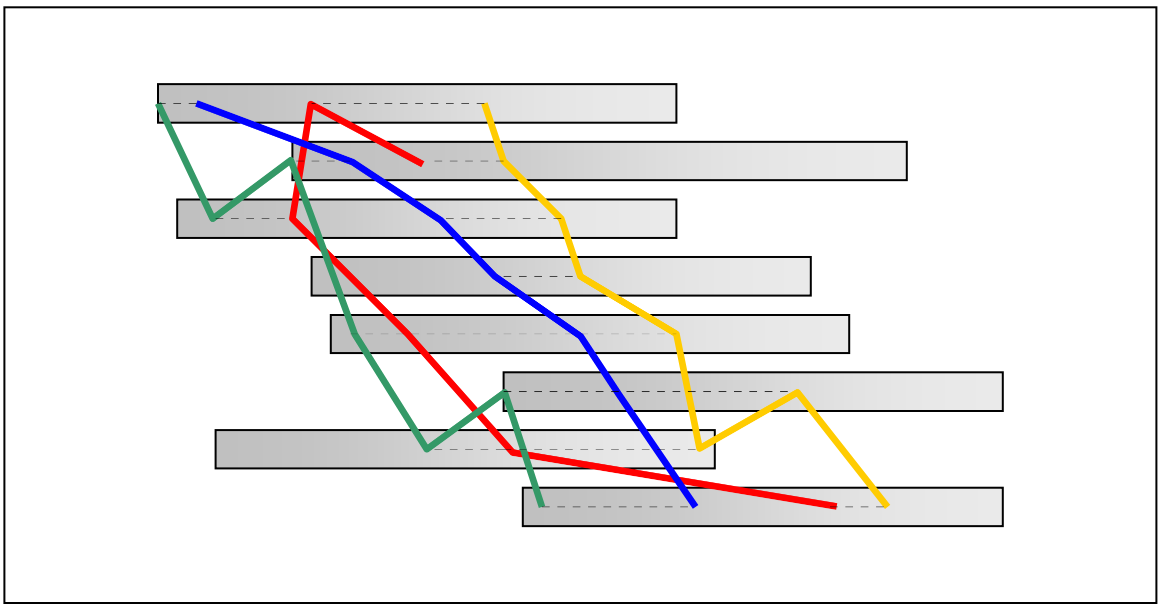


Figure 2.4: Crisscrossing in visiting the suppliers

Although crisscrossing relaxes time window constraints, crisscrossing may not be a good thing for the suppliers and the plant, especially when the parts are sequenced. Crisscrossing may significantly change the order of pickups at the suppliers and the order of arrivals at the plant. It requires both the suppliers and the plant to change the sequence of the shipments of parts and the receiving of parts, adding another layer of complexity to the problem that must be managed. Hong describes a sequencing operation in a case study where a large part of the value added is putting parts in the correct order (Hong, 2003). If crisscrossing is not important or can be readily managed, then GFR is a good formulation for JSS. Otherwise, CFR with the option to drop a number of pickups may be the better approach.

In general, crisscrossing routes tend to exist in GFR. Given a route with a specific number of pickups and suppliers, if we assume that it is efficient, then it is the shortest route in the graph. Since the objective of GFR and CFR is to find the shortest route in the graph, it is reasonable to assume that the route will be generated by both algorithms. CFR presupposes that the route runs multiple times, but not in GFR. Suppose that the routes to these suppliers in GFR crisscross during their visits; then these routes are alternate shortest routes or the same route running in reverse. At high frequency (e.g., γ is small), routes tend to be time window constrained. Hence, having alternate shortest routes are normal. At low frequency, however, the routes are capacity constrained. Then, the only way the GFR routes can dominate the shortest route is to be the shortest route. Furthermore, CFR and GFR routes tend to be longer due to the sharing of small loads, especially at high frequency. Suppose then some of the GFR routes run in reverse; then the time window is better utilized with crisscrossing since the visits at the beginning of the normal route may go at the end of the reverse route. The suppliers in the middle of the route are likely to clash, if these routes have the same number of nodes. However, it is possible to simply dropping a number of visits on the route without increasing the route cost. In this way, GFR routes compliment one another, resulted in highly complex pickup sequences. In summary, we expect that GFR routes will be more complex and less “organized” than CFR routes but more efficient. We can confirm this behavior by studying the results of GFR route designs when we solve the formulation.

2.1.4 Solution Methodology for GFR

In this research, a taboo search meta-heuristic is used to solve GFR. The complexity created by GFR prohibits use of the exact formulation approach of column generation approach as outlined in the VRPTW literature since routing by simply prescribing the first route of the cycle, like CFR, is no longer viable. (Indeed, even in the much simpler formulation of CFR we were not able to solve realistically sized problems using column generation approaches.) Furthermore, the column generation approach cannot guarantee an optimum integral solution. For an example, some relatively small problems in VRPTW still cannot be solved by this approach (J. F. Bard et al., 2002). On the other hand, a meta-heuristics, such as the taboo search approach, overcomes the complexity of GFR by making an extensive used of adaptive memory in a systematic manner. The solution is not optimum, but this approach is faster and more practical. In the next section, we discuss our implementation of taboo search. Additional details on the meta-heuritics approach used in solving GFR and the other formulations in this chapter can be found in Appendix B of this dissertation.

2.1.5 Generating the Initial Solution for the Taboo Search Strategy

Because CFR solutions may be feasible solutions of GFR, they are used here as the initial solutions of GFR. A conversion from CFR to GFR involves spreading the CFR routes, according to their pickup frequencies, over the supplier time windows, where each of the new routes has a pickup frequency of one. The new routes are widely spaced, time wise, to create the best possible heijunka. If the time window is too narrow too fit in all the routes, some routes are dropped by reducing the CFR routes' pickup frequencies. Normally, this should not happen, but there are cases where some suppliers have too many part sources but not enough time window. The way to deal with this special case in CFR is to increase γ and force the pickup frequency down. Dropping routes and reducing pickup frequency will cause the amount of allocated space per pickup to increase and potentially cause the solution to violate the space limit on the trailer. Nevertheless, starting an infeasible solution with good heijunka is easier than starting a solution with bad heijunka, which is still infeasible but satisfies the space constraints, since the visiting times of the routes are harder to plan than capacity allocation. The space constraints will be feasible again once the algorithm increases the number of pickups later in the solution. An ant colony optimization approach has been developed in this dissertation as an improved approach to solving CFR and it is discussed in Section 2.2.

2.1.6 Taboo Search Techniques - cross-exchange

The primary mode of neighborhood search in GFR is the cross-exchange. Cross-exchange has been used in taboo search for all VRP type problems, because they are natural for vehicle routing. In fact, the algorithm's cross-exchange loop structure for GFR is the exact copy of the loop structure for VRPTW. The only difference is the criteria that must be satisfied in order to make an acceptable exchange since the GFR algorithm has to consider the space and heijunka constraints in addition to the load and time window constraints considered by VPRTW. (For a general description of cross-exchanges, see Appendix B).

The taboo list of GFR tracks the solution cost to prevent repeating the same exchange in a cyclic manner. Ideally, a unique key to the solution should be used, such as a checksum or a hash signature. Nevertheless, the solution cost is, in most cases, unique for a non-structured graph with many variable distances. In the worst case, a branch of solutions is unfairly cut of from consideration due to its mistaken taboo status, which may be recovered from the search after the error status is dropped from the taboo list.

2.1.7 Taboo Search Techniques - checking Heijunka

A cross exchange sometimes invalidates the current feasible solution due to bad heijunka. To check for heijunka is difficult and costly, as it requires a single access to the time windows of all suppliers on the routes. We first construct the band of time, also known as interval time, for every visit on the route. Then, all visiting times that have been used are marked off from the band, except for the two routes under consideration. This requires a single check on the time of visits for all the routes in the solution. Finally, the best time is selected for the new routes based on the criterion of maximizing the interval between visits at every supplier. In our algorithm, each band of time is a *set* or a red-black binary tree, implementing the interval time's data structure.

2.1.8 Taboo Search Techniques - adding and dropping a pickup

For a fixed number of pickups, the total space utilized is fixed. To improve or relax the space constraint, adding or dropping, respectively, pickups is required. To prevent repeatedly adding and dropping the same supplier, another taboo list is attached to this function. For the adding function, the new pickup is a new route. For dropping, a pickup that violates heijunka constraint the most and costs the most is removed. From an algorithm design point of view, adding an independent taboo list to the algorithm may not be the best approach for managing the adding and dropping of pickups, as the two taboo lists have only an indirect way of tracking the status of one another. From the practical point of view, however, the approach is easy to implement and, in general, quite efficient.

2.1.9 Implementation and Results

The Taboo Search approach above has been implemented with Microsoft Visual C/C++ Compiler on an Intel Pentium III 450Mhz computer running Microsoft Windows XP Professional operating system. We applied a unified technique described in Appendix B, where the GFR solver is built on top of our current CFR and VRP algorithms. The program is object-oriented and complies with the ANSI C++ standard. It also compiles under GNU g++ with the University of Kentucky's HP Superdome supercomputer.

Table 2.4 gives the input parameters of a randomly generated problem with 10 part sources, where each part source has a different supplier. MIN FREQ and MAX FREQ are the minimum acceptable frequency and maximum acceptable frequency, respectively. Parameters for the objective function are $\beta_i = 0$, for all i (hence, we are only concerned with transportation cost minimization). The X and Y columns are the coordinates of the suppliers in the graph. Travel distances are generated from these coordinates.

Table 2.4: The Input Parameters of a Random Generated Problem

CAPACITY	MIN FREQ	MAX FREQ					
25	1	8					
PART SOURCE	SUPPLIER	LOAD	READY	DUE	SERVICE	X	Y
0	0	0	0	3500	0	50	50
1	1	3	778	1776	46	33	99
2	2	8	604	1683	47	82	18
3	3	13	666	1927	58	26	68
4	4	7	614	2276	56	91	60
5	5	6	732	1621	86	88	41
6	6	11	772	1544	45	10	0
7	7	16	608	1744	64	41	56
8	8	18	688	1945	27	26	93
9	9	3	755	1922	31	85	91
10	10	12	695	1719	34	62	53

First, let us look at a high frequency condition. The GFR solution for the random generated problem with $\gamma = 27$ is shown in Table 2.5 below. The solution has a cost of *1070.14* and used up *26.9667* units of space provided. Note that the routes are crisscrossing and organized in a way that compliments each other, in particular, node *7* and node *10*. Node *7* exists in every route, but sometimes as the first pickup and sometimes as the last. Node *10* that exists in four of the five routes displays the same behavior, but it is always visited at the opposite end of a given route from node *7*.

Table 2.5: The GFR Solution of a Random Generated Problem at $\gamma = 27$

```
TABOO SEARCH

SOLUTION COST: 1070.14                              NUMBER OF VEHICLES: 5
SPACE USED: 26.9667                                          COMPUTATIONAL TIME: 644 S

ROUTE: 0-10(781)-2(965.797)-5(1036.57)-4(1141.8)-9(1229.38)-1(1312.99)-8(1368.21)-3(1420.21)-7(1497.42)-0
ROUTE: 0-10(1144.4)-3(1217.4)-7(1294.6)-0
ROUTE: 0-6(932.581)-2(1051.8)-5(1122.57)-4(1227.8)-9(1315.38)-1(1398.99)-8(1454.21)-3(1506.21)-7(1583.42)-0
ROUTE: 0-7(954.703)-3(1037.91)-6(1165.77)-2(1284.99)-10(1372.3)-0
ROUTE: 0-7(820.192)-3(903.401)-8(986.401)-4(1316.94)-5(1392.17)-10(1506.81)-0

0 = ORIGIN, TIME IN BRACKET ()
```

Figure 2.5 below shows the routes of the GFR solution in a graph. Each line in the graph is a route with a frequency of one. The dark blue circles are the suppliers. The plant is the pink square located at *(50, 50)*.

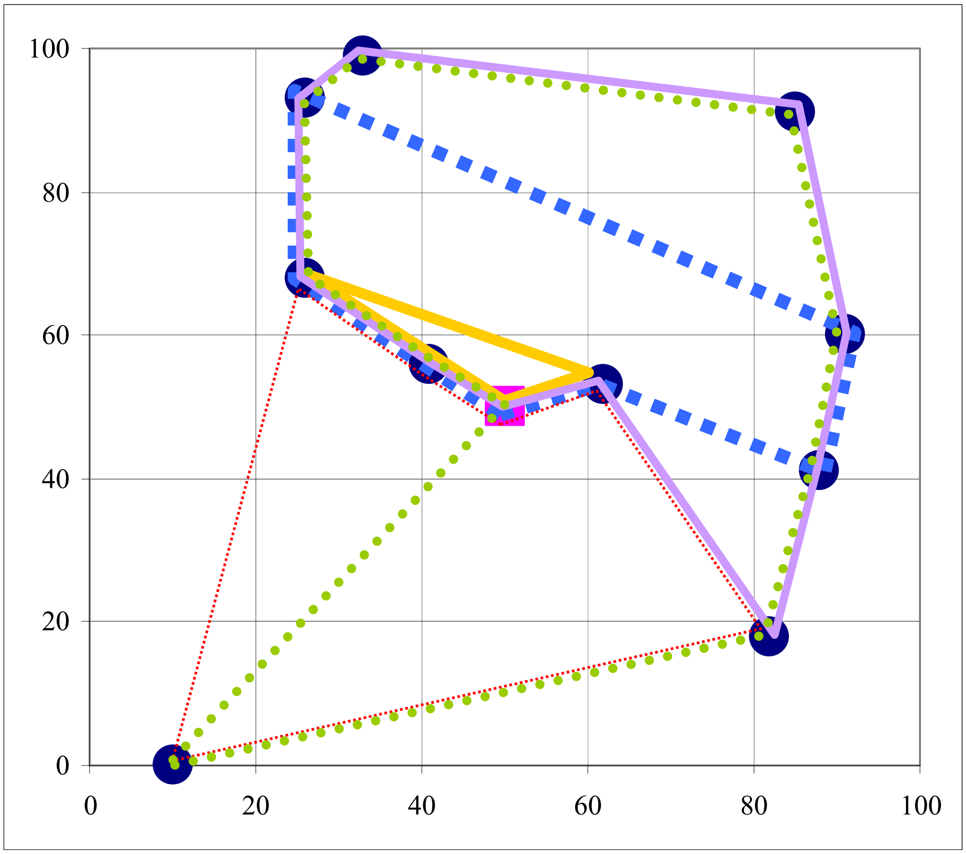


Figure 2.5: The GFR Solution of a Random Generated Problem at $\gamma = 27$

As a comparison, the CFR solution in Table 2.6 below is given by the ant colony optimization algorithm described in Section 2.2. (The same solution was also obtained by the taboo search approach in Chuah and Yingling, in press.) Note that the CFR solution requires more vehicles than GFR and costs more, all of these for the price of nicely ordered, repeated routes. Moreover, the solution is obtained in a relatively short amount of computational time. The cost difference is about 6.1% and one would want to question whether the complexity of GFR is worth the cost savings.

Table 2.6: The CFR Solution of a Random Generated Problem at $\gamma = 27$

ANT - TABOO SEARCH	
SOLUTION COST: 1137.49 SPACE USED: 27	NUMBER OF VEHICLES: 9 COMPUTATIONAL TIME: 6 S
FREQ: 3 ROUTE: 0-6-2-5-4-9-1-8-3-7-0	FREQ: 6 ROUTE: 0-10-0
0 = ORIGIN	

Figure 2.6 below is the routes of the CFR solution in a graph.

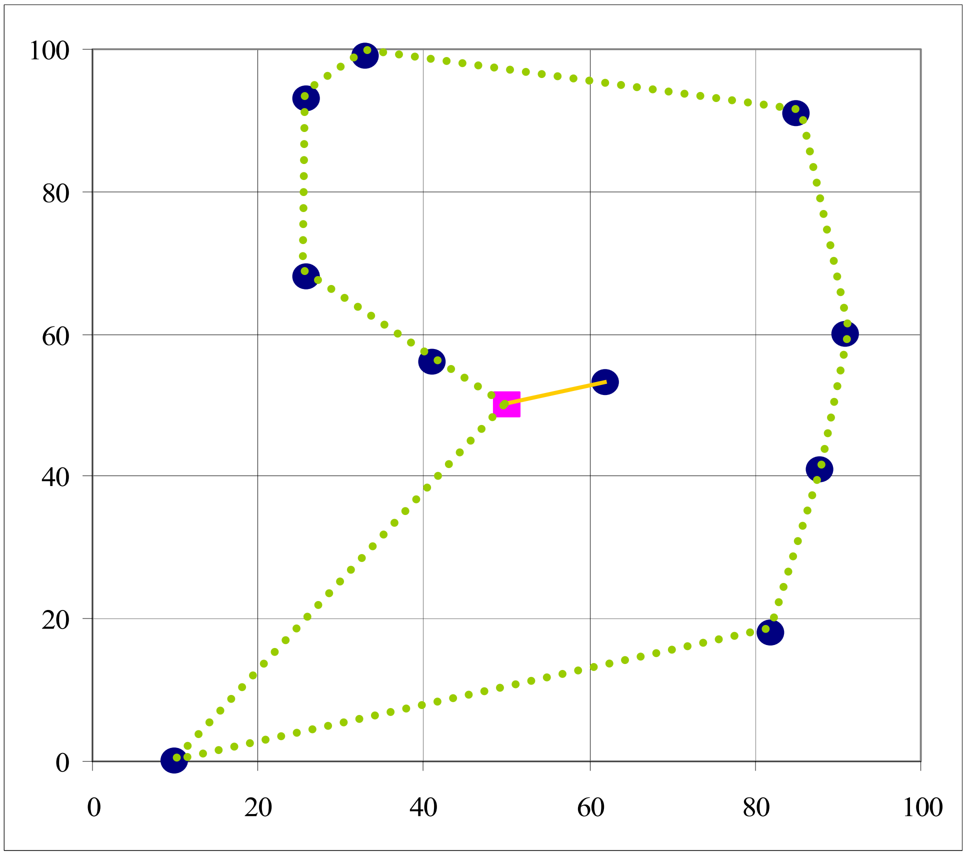


Figure 2.6: The CFR Solution of a Random Generated Problem at $\gamma = 27$

Now, let us look at behaviors under low frequency conditions. First, note that $\gamma = 87$ is the maximum amount of space the problem can ever have. That is, the constraint involving γ is non-binding when $\gamma > 87$. The solution for this case is essentially a VRPTW solution (where each route is run with a frequency of 1) and is shown in Table 2.7 below. Moreover, the solution cost of 462.111 is the lowest cost for this problem, based on the results of all our algorithms.

Naturally, even GFR gives this solution. Therefore, to study the system under low frequency conditions requires $\gamma < 87$.

Table 2.7: The VRPTW-like Solution of a Random Generated Problem at $\gamma = 87$

ANT-TABOO SEARCH	
SOLUTION COST: 462.111	NUMBER OF VEHICLES: 4
SPACE USED: 87	COMPUTATIONAL TIME: 1 S
FREQ: 1 ROUTE: 0-2-5-4-9-0	
FREQ: 1 ROUTE: 0-1-8-3-0	
FREQ: 1 ROUTE: 0-7-0	
FREQ: 1 ROUTE: 0-10-6-0	
0 = ORIGIN	

Figure 2.7 below shows the solution in a graph. The number beside each node in the graph is the loads, i.e. the number of parts.

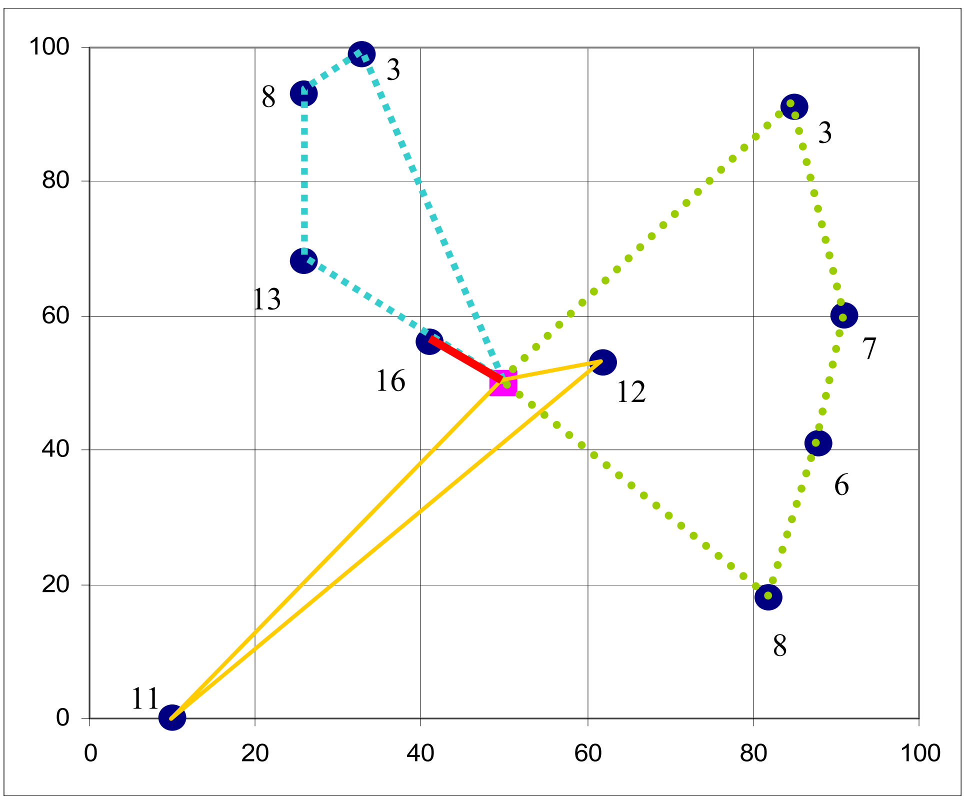


Figure 2.7: The VRPTW-like Solution of a Random Generated Problem at $\gamma = 87$

Table 2.8 below shows the GFR solution with $\gamma = 67$. The same result is given by CFR, although one of the routes has a pickup frequency of two.

Table 2.8: The GFR Solution of a Random Generated Problem at $\gamma = 67$

TABOO SEARCH	
SOLUTION COST: 548.712	NUMBER OF VEHICLES: 4
SPACE USED: 66.5	COMPUTATIONAL TIME: 30 S
ROUTE: 0-6(772)-2(891.216)-5(961.986)-0	
ROUTE: 0-4(614)-9(755)-1(838.612)-8(893.831)-0	
ROUTE: 0-7(608)-3(691.209)-10(788.209)-0	
ROUTE: 0-7(694)-3(777.209)-10(874.209)-0	
0 = ORIGIN, TIME IN BRACKET ()	

Figure 2.8 below shows the GFR solution with $\gamma = 67$. The solid orange route has a frequency of two. The other two routes have frequency of one.

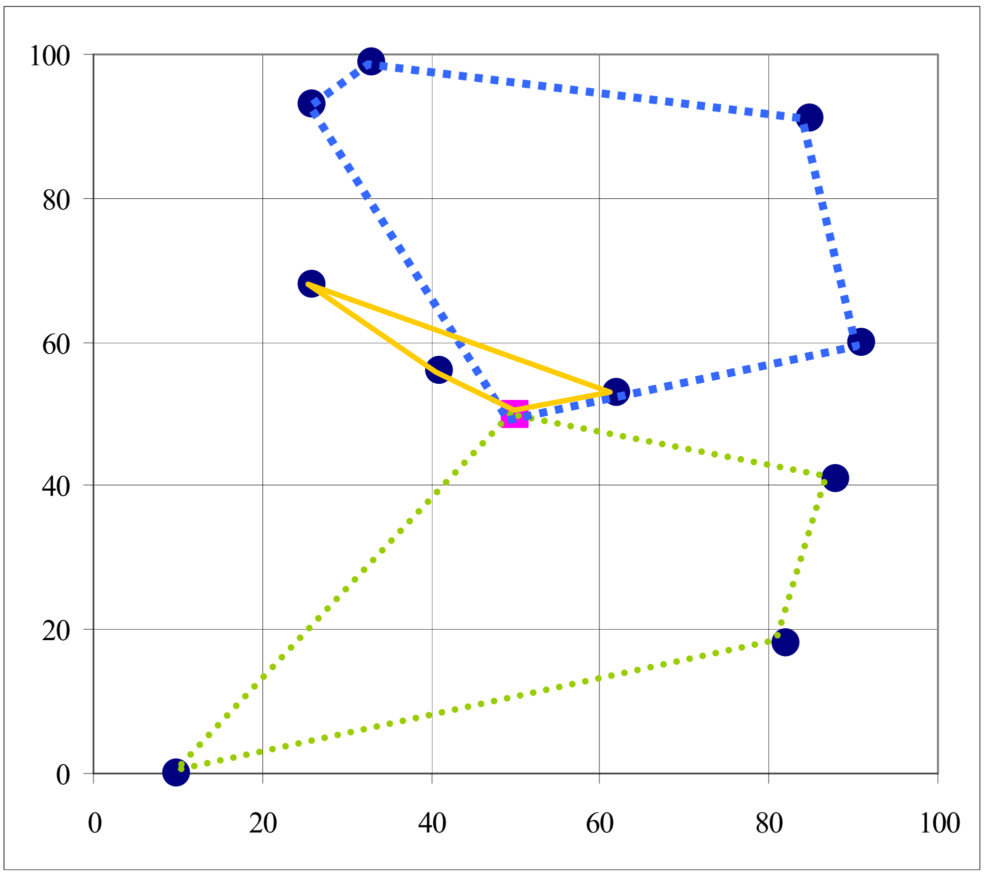


Figure 2.8: The GFR Solution of a Random Generated Problem at $\gamma = 67$

Table 2.9 below shows a GFR solution with $\gamma = 47$. The routes in this solution are still quite organized, except that there is a crisscross between node *7* and node *10*. Nevertheless, it can be fixed quite easily without affecting the solution cost. Note that while experimenting with different parameters of the GFR algorithm for this solution, the quality of the solution depends highly on the initial solutions. This means that the current algorithm as implemented still has difficulties in finding good solutions in this region.

Upon further investigation, we also find that the algorithm spends a significant amount of time searching in the region when γ *is* a lot less than *47*. γ in the current solution is determined by the sum of the number of pickups for each part source. It seems that the algorithm some difficulties in adding and removing pickups.

Table 2.9: The GFR Solution of a Random Generated Problem at $\gamma = 47$

TABOO SEARCH	
SOLUTION COST: 700.809	NUMBER OF VEHICLES: 5
SPACE USED: 46.3333	COMPUTATIONAL TIME: 67 S
ROUTE: 0-7(1012)-6(1158)-10(1305.12)-0	
ROUTE: 0-3(666)-8(749)-1(785.22)-9(883.831)-4(946.407)-5(1021.64)-2(1131.41)-0	
ROUTE: 0-10(1191.89)-7(1247.11)-0	
ROUTE: 0-7(694)-0	
ROUTE: 0-3(752)-8(835)-1(871.22)-9(969.831)-4(1032.41)-5(1107.64)-2(1217.41)-0	
0 = ORIGIN, TIME IN BRACKET ()	

Figure 2.9 below shows the GFR solution with $\gamma = 47$. The orange route has a frequency of two.

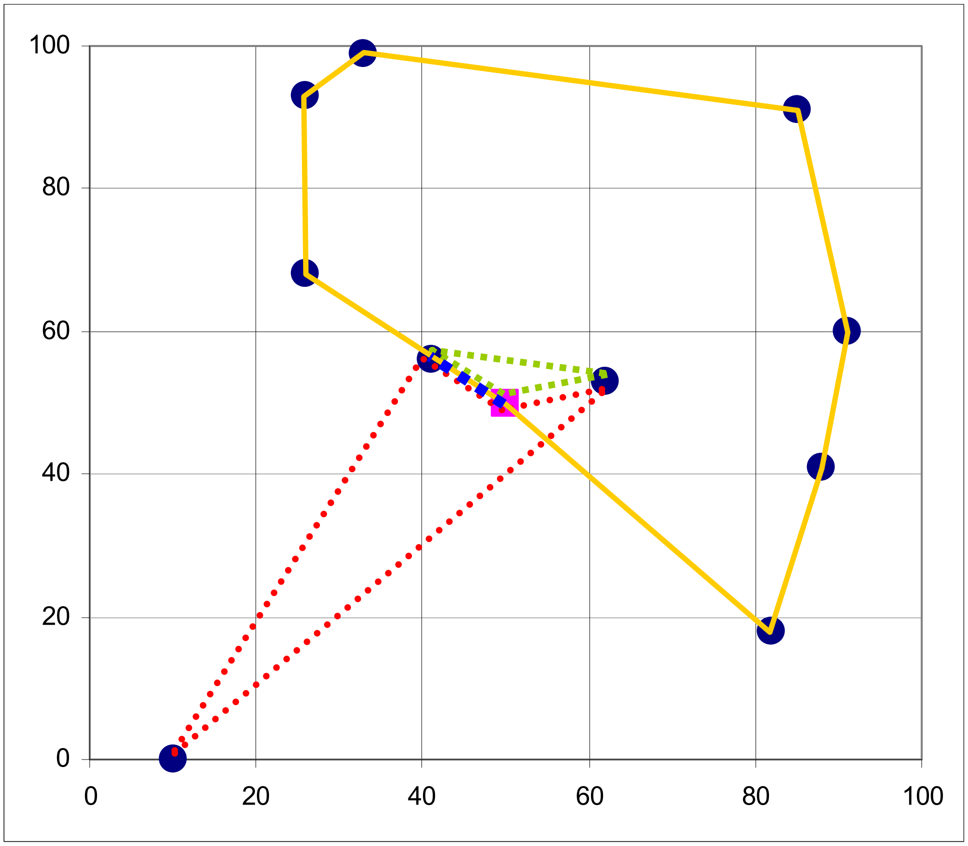


Figure 2.9: The GFR Solution of a Random Generated Problem at $\gamma = 47$

As a comparison, the CFR solution in Table 2.10 below is obtained by taboo search.

Table 2.10: The CFR Solution of a Random Generated Problem at $\gamma = 47$

TABOO SEARCH	
SOLUTION COST: 715.773	NUMBER OF VEHICLES: 4
SPACE USED: 46.3333	COMPUTATIONAL TIME: 11 S
FREQ: 3 ROUTE: 0-7-0	
FREQ: 1 ROUTE: 0-6-0	
FREQ: 2 ROUTE: 0-10-0	
FREQ: 2 ROUTE: 0-2-5-4-9-1-8-3-0	
0 = ORIGIN	

Figure 2.10 below shows the CFR solution with $\gamma = 47$. Node *6*, *7*, and *10* in the graph cannot be combined into one route because each route has a different frequency. Running these three nodes in one route at a frequency of three is more expensive.

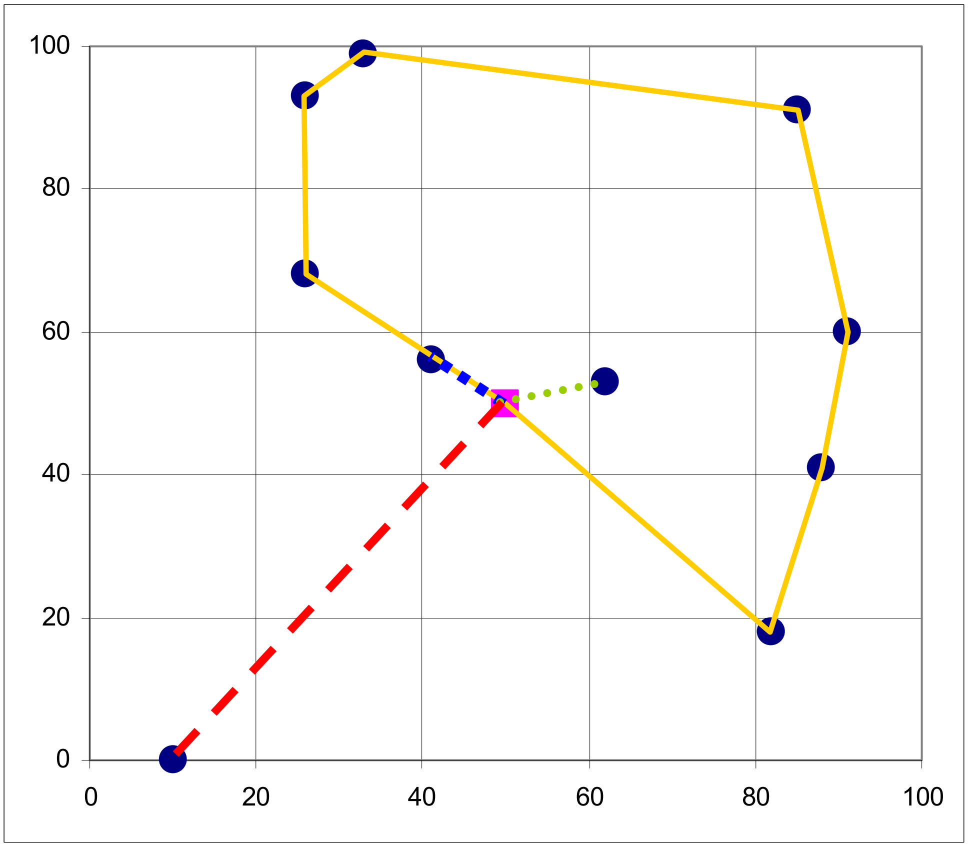


Figure 2.10: The CFR Solution of a Random Generated Problem at $\gamma = 47$

The solutions comparing GFR and CFR for $\gamma = 27$ has been shown previously. The cost difference between GFR and CFR has decreased from 6.1% for $\gamma = 27$ to 2.1% for $\gamma = 47$. At low frequency, as we saw, there is no different in cost.

In summary, the impact of CFR restrictions is minimal and in some cases, because they simplify route designs and management of the system, desirable. The GFR algorithm implemented still has room for improvements. It has problems in assigning visiting time to the routes, as well as in managing the space constraint through the process of adding and dropping of pickups.

2.1.10 Statistical Analysis of 30 Random Problems

To verify the gain of GFR over CFR, 30 random problems are generated. 10 of the problems are size 10 (i.e. 10 suppliers), 10 are size 20, and the rest are size 30. Each of the problems is tested with the GFR algorithm and the CFR algorithm. At the same time, we vary γ between small, medium, and the maximum limit to generate 3 cases for each problem. Thus, the total number of cases is 180. From these cases, the solution costs, inventory, and computation times are averaged for comparisons.

Figure 2.11 below shows the comparisons of size 10 problems between CFR and GFR algorithm. At $\gamma = 27$, the GFR algorithm fails to find solution for 3 of the 10 cases. The respective CFR solutions of these problems have been omitted. Nevertheless, we see that the GFR solutions cost less than the CFR solutions.

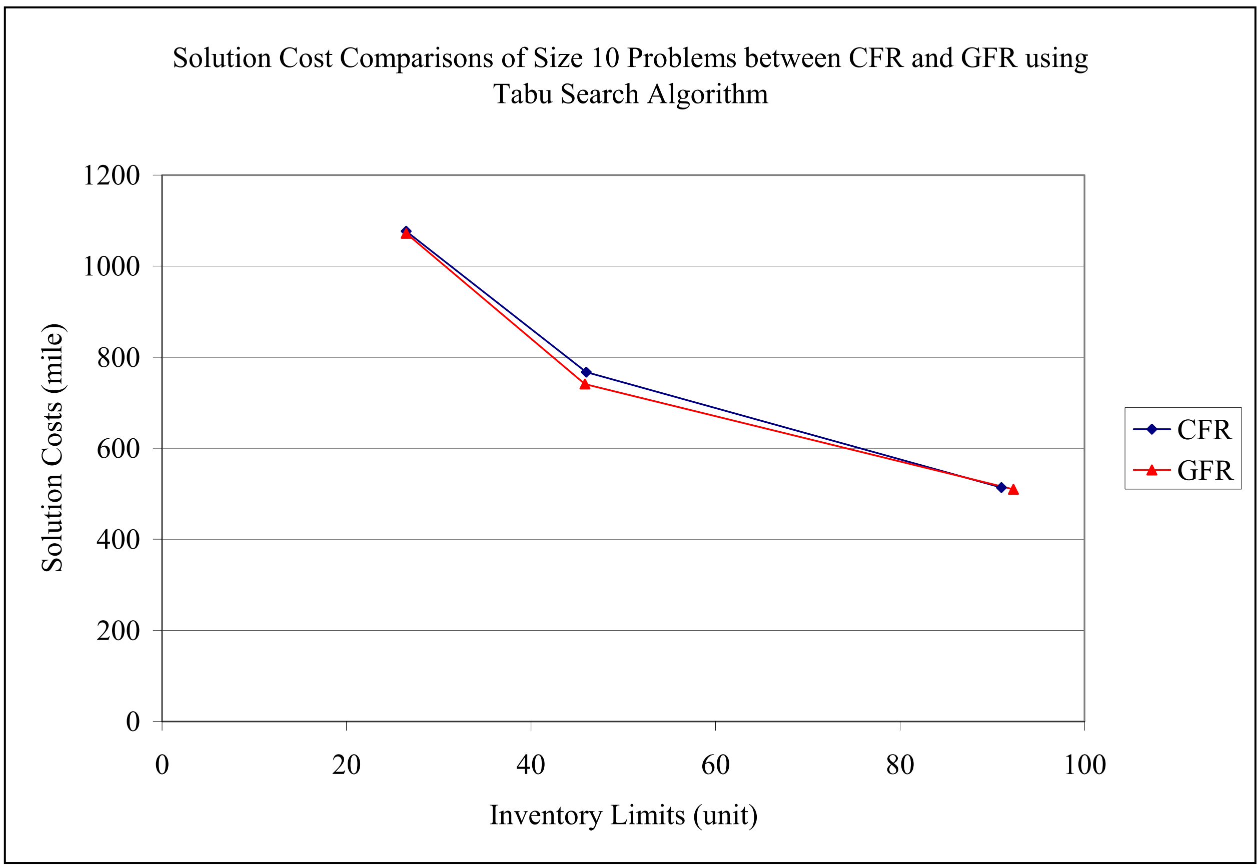


Figure 2.11: The cost comparisons of 10 size 10 problems between CFR and GFR

Figure 2.12 below shows the comparisons of size 20 problems between CFR and GFR algorithm. At $\gamma = 60$, the GFR algorithm fails to find solution for 8 of the 10 cases. The respective CFR solutions of these problems have been omitted. Like before, we see that the GFR solutions cost less than the CFR solutions.

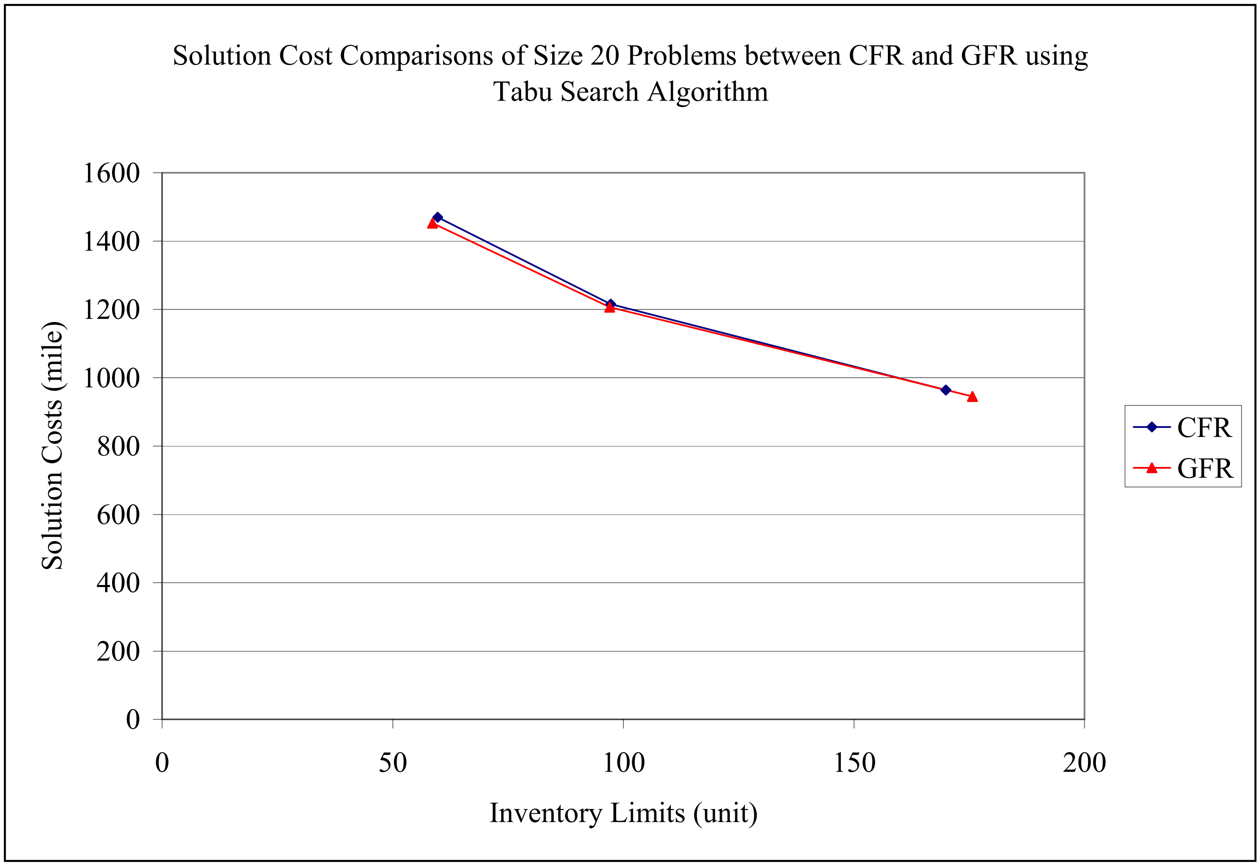


Figure 2.12: The cost comparisons of 10 size 20 problems between CFR and GFR

Figure 2.13 below shows the comparisons of size 30 problems between CFR and GFR algorithm. We see that on average the GFR solutions cost less than the CFR solutions.

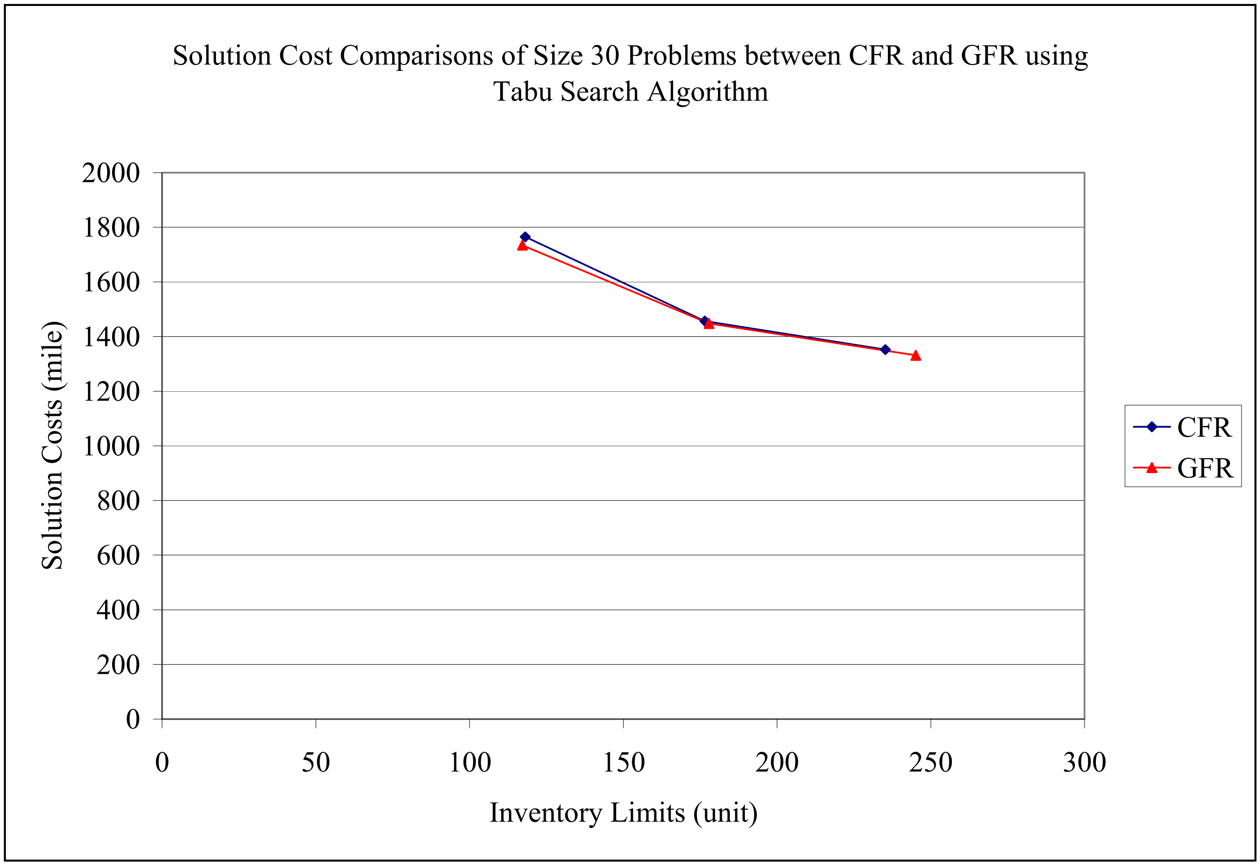


Figure 2.13: The cost comparisons of 10 size 30 problems between CFR and GFR

Figure 2.14 below shows the percentage different in costs between CFR solutions and GFR solutions. The GFR solutions cost about 1.4% less than the CFR solutions. The Y error bars show the standard deviations of the respective averages. It appears in general that GFR solutions do not offer major economic advantage over CFR solutions.

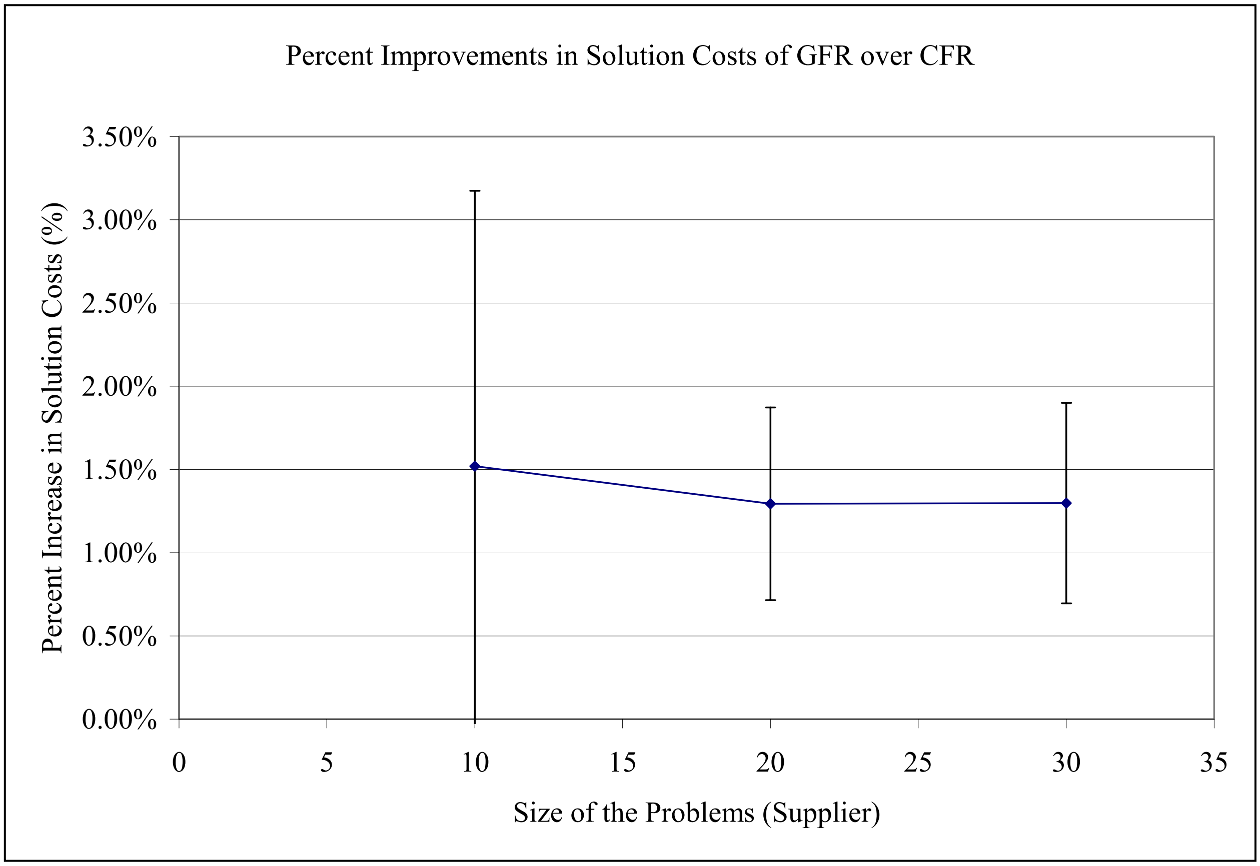


Figure 2.14: The percentage different in costs between CFR solutions and GFR solutions

To illustrate practical limits on the size of GFR problems than can be solved by the GFR algorithm, we have measured the computational times it takes for the algorithm to find the solutions. Note that the computational times depend on the performance of the computer and the termination conditions. Theoretically, better solutions can be found if the maximum number of iterations and the maximum number of iterations with no improvements are larger. In this case, the computer is Pentium III 450 MHz and the maximum number of iterations and the maximum number of interations with no improvements are 2000 and 500, respectively.

Figure 2.15 below shows the averaged GFR algorithm computational times for the three different sizes of problems.

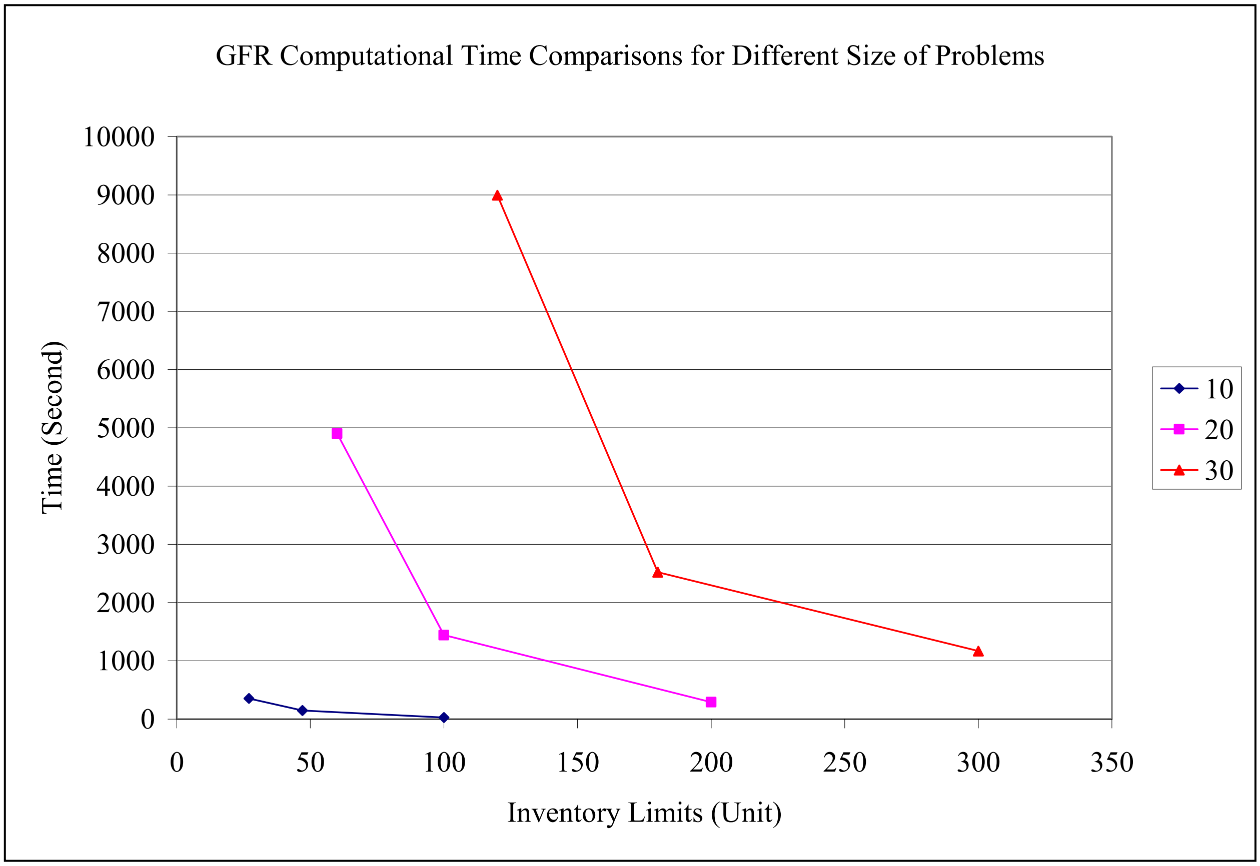


Figure 2.15: The computational time the GFR algorithm takes to find the solutions

2.2 Ant Colony Optimization (ACO) of Common Frequency Routing Problem

This research studies the potential of ACO to improve the existing taboo search (TS) algorithm for CFR. At the same time, it supplies basic functionality for building a GFR algorithm as explained in Section 2.1.

As noted earlier in Section 2.1, the common frequency routing problem (CFR) is a vehicle routing problem that permits only one route to visit a part source, instead of multiple routes, but, in contrast to GFR, a route can be repeated to perform multiple pickups. CFR has a global space/inventory constraint that effectively reduces the number of parts per pickup in the routes. Thus, multiple pickups are required to satisfy this constraint. A detailed explanation of the CFR formulation can be found in Chuah (2000) and Chuah and Yingling (in press). Moreover, see Section 2.1.2 for a statement of this formulation.

Ant colony optimization (ACO) has been used to solve VRP and VRPTW with good results (Dorigo and Caro 1999; Gambardella, et al. 1999). An extension of ACO to CFR is natural but not trivial. Handling the pickup frequency of CFR requires a new heuristic algorithm within the structure of ACO. In the next section, we describe an approach to solve CFR using ACO.

2.2.1 Methodology - ACO structure

In an attempt to unify meta-heuristics algorithms, our ACO implementation for CFR follows the same general structure as the ACO for VRPTW described in Dorigo and Caro (1999) and Gambardella, et al. (1999). First, the algorithm initializes a number of ants or search agents. Each ant in ACO builds a solution by adding nodes one-by-one into an empty sequence, S, until S contains all the nodes in the graph. The first and the last node of S is always the origin; the selection of the next node at each step depends on the feasibility of each node and the *pheromone graph* as will be explained below. At any time during the building process, the sequence may add the origin as the next node, which indicates the end of the current route, or add another node not in S.

2.2.2 Methodology - pheromone graph

The purpose of the pheromone graph is to provide the weights for deciding which node to select at each step. The pheromone graph consists of a set of values on the arcs of the graph, specifying the desirability of these arcs in relation to one another. Our implementation of the pheromone graph does not differ very much from those in the literature (see Gambardella, et al. 1999) and described below for reference.

When deciding which node to add, ACO first searches the neighborhood for all the feasible nodes, F. Then, a closeness factor, c_{ij}, is determined; where the index, i, is the current node and $j \in F$. The probability of a node j being selected is given by:

$$p_j = x * a_{ij} / (c_{ij})^w + (1 - x) * m_j$$

where x is the exploration percentage, a_{ij} is the current pheromone level, w is the closeness weight constant, and $m_j = \{ 1 \text{ if } j = \arg\{f(j) = \min\{ a_{ij} / (c_{ij})^w\}, j \in F\} \text{ and } 0 \text{ otherwise}\}$. We see that the higher the pheromone level to node j and the closer node j, the more likely we are to select node j. x is used to control the degree that these two factors control the search.

The graph is updated at two points: during the solution building process and after an ant finishes building a solution. At each step during the solution building process, the pheromone level of the relevant arc between the current node and the next node is changed by the ant according to the following formula:

$$a_{ij} = (1 - e) * a_{ij} + e * t_{ij}$$

where i is the current node, j is the next node, e is the evaporation percentage, and t_{ij} is the initial pheromone level.

After an ant completes a solution, the graph is updated with the following formulas:

$$a_{ij} = (1 - e) * a_{ij} \qquad \text{for all } i \text{ and } j.$$

and

$$a_{ij} = a_{ij} + e / c \qquad \text{for all } (i, j) \text{ in } B$$

where B is the best solution and c is the cost of the best solution. Hence, we see that the pheromone level increases for arcs in the best solution and decreases for the other arcs.

2.2.3 Methodology - balancing the space constraint and the frequency

In VRP, the closeness factor is simply the distance between two suppliers. In VRPTW, the closeness factor takes into account the time window at the supplier. That is as the current time approaches the closing time of a supplier's time window, the closeness factor to that supplier is reduced, i.e. improved.

In CFR, the closeness factor should also consider the space constraint and the pickup frequency. Note that if the frequencies of all pickups are fixed, the total space used is also fixed. If ACO designs the early routes in the solution at low frequencies, then the rest of routes need to run at a higher frequency. Hence at every step where ACO completes a route, i.e. $i = o$, an average frequency, f_{avg}, is calculated such that the total space used does not exceed the maximum space. The average frequency adjusts the closeness factor such that if adding a particular node resulted in a reduction of frequency of an entire route, then the closeness factor associated with this node is increased, proportional to a total space penalty constant per pickup. The equation for the average frequency is given below:

$$f_{avg} = \frac{\sum_{i \notin S} D_i}{\gamma - \sum_{i \in S} \frac{D_i}{f^k}}$$

where γ is the maximum space, D_i is the load pickup at node i, and f^k is the frequency of route k, associated with i in S.

There are also some flexibility in determining the final frequency of the route at $i = o$. A straightforward approach is to set the integer frequency closest to the average frequency:

$$f^k = \{f, \text{ such that } f = \min\{|f - f_{avg}|\} \text{ and } f_{min} \leq f \leq f_{max}\}$$

where f_{min} and f_{max} are, respectively, the minimum and maximum frequency such that the time window constraints at all the pickup points in the route are not violated. As an extension, we can also perturb the frequency according to a probability factor and the average cost of the route per pickup.

$$f^k = \{f, \text{ such that } f = \min\{|f - f_{avg}|\} + x * p \text{ and } f_{min} \leq f \leq f_{max}\}$$

where x is the probability factor and $p = \{ 1 \text{ if } c^k / n^k < \Sigma (c^k / n^k) \text{ and } -1 \text{ otherwise}\}$. c^k and n^k are the cost and the number of visits of route k. The perturbation widens the search of the local neighborhood, and therefore improves the search results at the cost of more computations.

2.2.4 Methodology - local search procedure

Due to the perturbation of frequency, as well as the random numbers, the final solution of an ant search may not be feasible. To regain the feasibility of the solution, we attached a TS algorithm at the end of the solution building process. Then, the TS improved solution is used to update the pheromone graph. To ensure that the TS algorithm does not dominate the search, it has a relatively weak termination criterion.

2.2.5 Implementation and Results

The ACO approach above has been implemented with Microsoft Visual C/C++ Compiler on an Intel Pentium III 450Mhz computer running Microsoft Windows XP Professional operating system. The program is object-oriented and complies with the ANSI C++ standard. It also compiles under GNU g++ with the University of Kentucky's HP Superdome supercomputer.

The CFR solutions for the random generated problem (R1) with $\gamma = 1000$ is shown in Table 2.11 below. The input file for this problem is in Appendix C.

Table 2.11: A Comparison of CFR Solutions between Taboo Search and Ant Taboo Search

TABU SEARCH	ANT-TABU SEARCH
FREQ: 2 ROUTE: 0-3-49-59-0	FREQ: 8 ROUTE: 0-34-23-78-25-19-66-0
FREQ: 7 ROUTE: 0-67-50-8-11-26-78-0	FREQ: 6 ROUTE: 0-69-17-43-62-27-29-0
FREQ: 7 ROUTE: 0-91-85-76-32-0	FREQ: 6 ROUTE: 0-7-99-54-53-61-0
FREQ: 4 ROUTE: 0-21-6-65-40-62-0	FREQ: 8 ROUTE: 0-20-97-48-14-6-65-40-0
FREQ: 7 ROUTE: 0-20-97-48-14-43-17-0	FREQ: 4 ROUTE: 0-73-37-81-51-67-0
FREQ: 3 ROUTE: 0-57-83-0	FREQ: 4 ROUTE: 0-13-39-42-77-0
FREQ: 7 ROUTE: 0-66-19-25-23-33-34-0	FREQ: 7 ROUTE: 0-86-4-55-70-46-88-0
FREQ: 6 ROUTE: 0-69-27-29-36-28-0	FREQ: 5 ROUTE: 0-18-96-9-79-0
FREQ: 8 ROUTE: 0-80-30-52-16-74-41-89-0	FREQ: 3 ROUTE: 0-56-22-94-15-98-0
FREQ: 6 ROUTE: 0-24-77-39-42-60-0	FREQ: 8 ROUTE: 0-80-30-52-16-74-41-89-0
FREQ: 4 ROUTE: 0-61-79-96-0	FREQ: 5 ROUTE: 0-57-83-71-90-0
FREQ: 6 ROUTE: 0-92-63-10-64-0	FREQ: 3 ROUTE: 0-84-95-0
FREQ: 3 ROUTE: 0-98-15-94-22-56-0	FREQ: 7 ROUTE: 0-32-76-10-63-92-0
FREQ: 5 ROUTE: 0-71-12-47-31-45-0	FREQ: 4 ROUTE: 0-59-60-24-3-49-0
FREQ: 7 ROUTE: 0-72-1-82-0	FREQ: 5 ROUTE: 0-38-87-2-0
FREQ: 8 ROUTE: 0-7-2-87-38-99-0	FREQ: 9 ROUTE: 0-91-36-28-72-1-82-0
FREQ: 4 ROUTE: 0-73-37-81-51-53-0	FREQ: 7 ROUTE: 0-75-35-44-68-100-58-0
FREQ: 7 ROUTE: 0-88-70-55-4-84-46-0	FREQ: 4 ROUTE: 0-21-85-64-0
FREQ: 5 ROUTE: 0-18-5-93-54-9-0	FREQ: 5 ROUTE: 0-33-50-8-26-11-0
FREQ: 10 ROUTE: 0-90-0	FREQ: 2 ROUTE: 0-5-93-0
FREQ: 5 ROUTE: 0-95-86-13-75-35-0	FREQ: 5 ROUTE: 0-47-31-45-12-0
FREQ: 5 ROUTE: 0-44-68-58-100-0	COST: 229047 VEHICLES: 21
COST: 232089 VEHICLES: 22	LOAD: 998.438 TIME: 1581.82
LOAD: 994.625 TIME: 487.731	

In general, the solutions given by ant taboo search, such as the solution in the table above, are better than the solutions given by taboo search alone. Nevertheless, it takes longer time to find the better solutions. It is hard to quantify how much better the ant taboo search is against the taboo search. Thus, 30 random problems are generated and tested with these two algorithms to show their performance on an average basis. Figure 2.16 below shows the solution cost comparisons between these two algorithms. For problems of size 10, the optimum CFR solutions are found. For larger problems, ant taboo search performs better with small γ. The ant taboo search has some premature termination problems with large γ because the algorithm parameters (exploration and evaporation) have been tailored for cases with small γ.

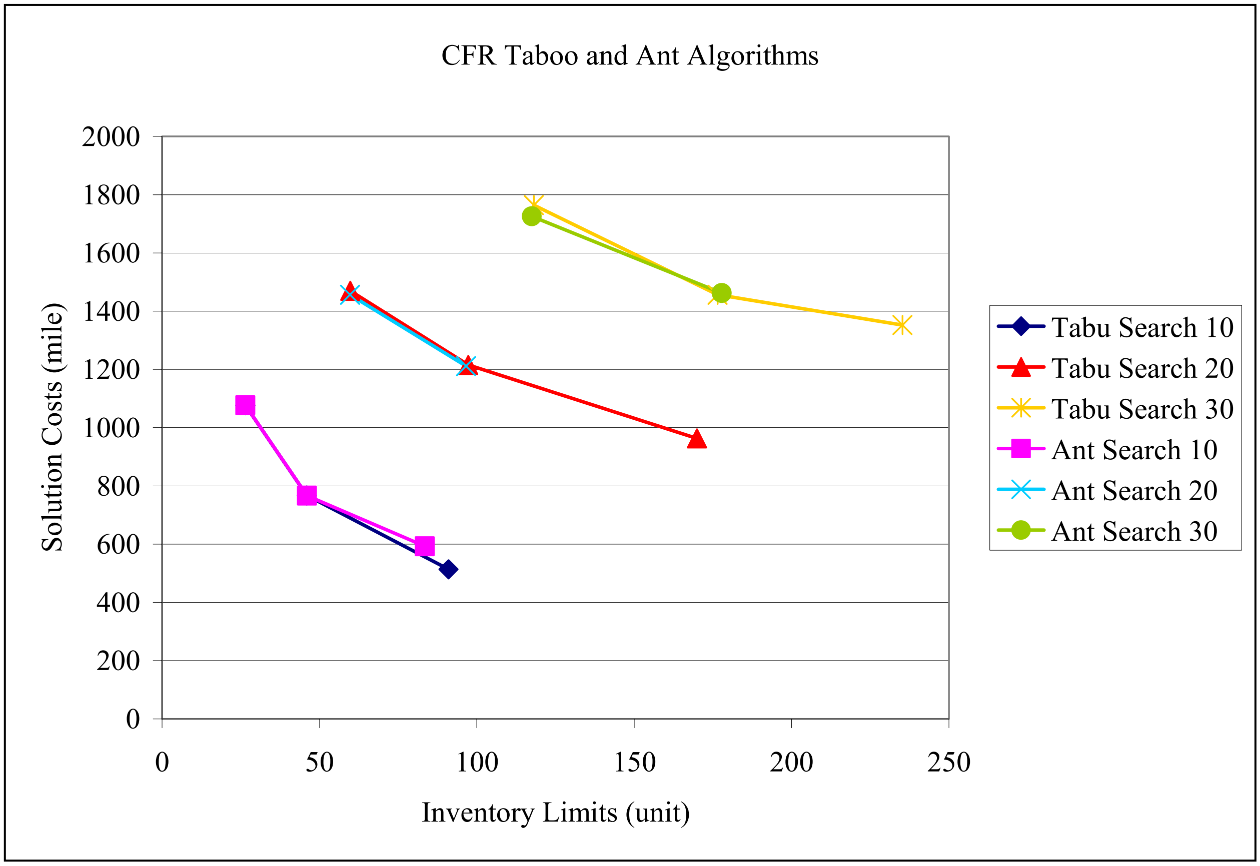


Figure 2.16: The cost comparisons between taboo search and ant taboo algorithm

Figure 2.17 below shows the difference in computational time between taboo search and ant taboo algorithm. The rate of increase in computational time for ant taboo algorithm is larger than the rate of increace in computational time for taboo search.

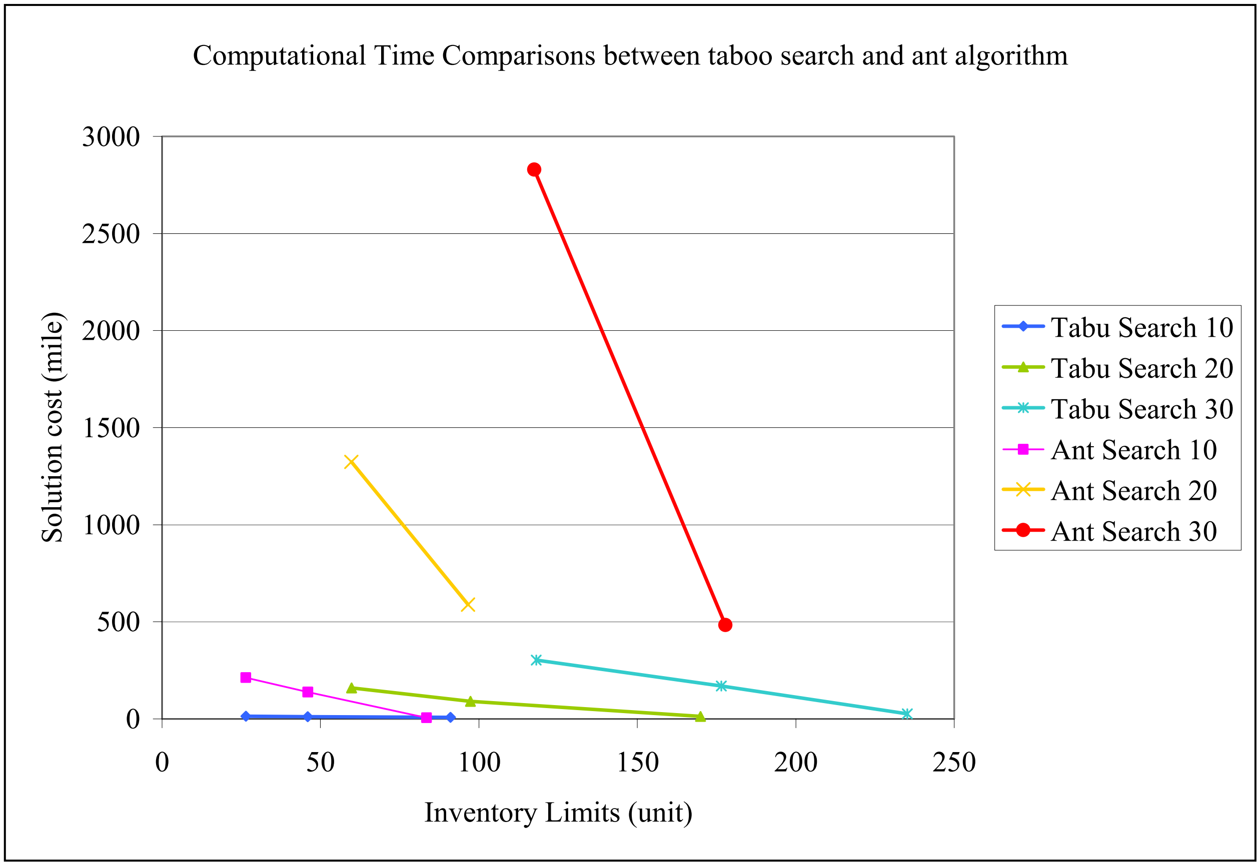


Figure 2.17: The time comparisons between taboo search and ant taboo algorithm

As for building an initial solution for the GFR, the optimum CFR solution sometimes works against the early exploration process of GFR, requiring the GFR algorithm to move away from this optimum CFR solution before any new improvement is made. Nevertheless, this may not be always the case. In Chapter 3, we will apply taboo search to a number of problems to study some characteristics and effects of common frequency routing.

2.3 Cross Dock Routing Problem

JSS uses cross-dock facilities if the situation permits. Cross-docking facilities placed in selected locations can improve shipping and handling by reducing the complexity of the routes and by effectively increasing the time windows that suppliers are open to the main plant (this is determined by the cross-dock hours which are at the discretion of the manufacturer). Note that cross-docks generally do not reduce the mileage for transportation while they increase the facilities and staffing required for JSS , Cross docks were used by Toyota as part of an integrated logistics system for serving their multiple North American plants, where the advantages above, particularly in part and supplier sharing among plants is most useful.

There are three ways to look at a cross-docking problem. In the first case, a two-tier approach, all suppliers that feed directly to the manufacturing plant itself are exclusively cross-dock suppliers. It is assumed that the assignment of the other suppliers to the cross docks has already been defined. The optimization approach consists of solving several mini routing problems, or the sub-routing problems (SRP), for each cross-docking facility. Then, the approach solves the routing for all the cross-docking facilities, also known as the main routing problem (MRP). MRP and SRP can assume any type of VRP, but CFR and GFR are more suitable for JSS.

In the second case, there are some direct suppliers that operate in the main routes and some cross-dock suppliers in the sub-routes. However, these suppliers are defined prior to optimization. Hence, the optimization approach is very similar to the first case, except that in MRP, there are a number of direct suppliers besides the cross-docking facilities.

In the third case, the status of the suppliers is not defined prior to optimization. This is the most general case and the focus of our discussion in the next section. In contrast to the first two cases, which are trivial applications of CFR optimizations, the third case requires some changes to the formulation. As with the first two cases, there is no restriction on the type of routing problems for the third case.

Note that in all of these cases, we assume that the sub routes are performed ahead of the main routes. Hence, when a main route visits a cross docking facility, the parts have already reached the facility.

2.3.1 Mathematical Formulations

To solve the general cross-dock routing (CDR) problem, we define the objective function as the sum of the sub-routes distances and the main routes distances. All suppliers are represented by a set of variables, where the number of variables in the set is equal to the number of cross-docking facilities plus one. Each set of variables has its own flow constraints and the resources constraints. An additional constraint is defined to restrict each supplier from being both a cross-docking supplier and a direct supplier. Another set of load constraints is required to account for the loads pickup by the cross-docking facilities.

Figure 2.18 below shows the cross-docking mathematical formulation with *n* cross-dock facilities and CFR routing policy:

Objective function : $$\min \sum_i \sum_j \sum_k f^k c_{ij} x_{ij}^k + \sum_i \sum_j \sum_k \sum_n f_n^k c_{ij} y_{n,ij}^k$$

variables:

$x_{ij}^k = \{0,1\}$

$y_{n,ij}^k = \{0,1\}$

$T_i^k \geq 0$

$T_{n,i}^k \geq 0$

$L_i^k \geq 0$

$L_{n,i}^k \geq 0$

$f^k \geq 0$

$f_n^k \geq 0$

crossdock flow :

$$\sum_j \sum_k x_{ij}^k + \sum_j \sum_k \sum_n y_{n,ij}^k \geq 1 \quad \forall i$$

$$\sum_k \sum_i x_{in}^k f^k \leq f_n^k \quad \forall k$$

main route flow:

$$\sum_i x_{ij}^k - \sum_i x_{ji}^k = 0 \quad \forall j, \forall k$$

$$\sum_i x_{io}^k = 1 \quad \forall k$$

$$\sum_i x_{oi}^k = 1 \quad \forall k$$

sub route flow:

$$\sum_i y_{n,ij}^k - \sum_i y_{n,ji}^k = 0 \quad \forall j, \forall k, \forall n$$

$$\sum_i y_{n,io}^k = 1 \quad \forall k, \forall n$$

$$\sum_i y_{n,oi}^k = 1 \quad \forall k, \forall n$$

main route space:

$$\sum_i \sum_j \sum_k D_i^k x_{ij}^k \leq \gamma$$

sub route space:

$$\sum_i \sum_j \sum_k D_i^k y_{n,ij}^k \leq \gamma_n \quad \forall n$$

main route time:

$$a_i \leq T_i^k \leq b_i - \tau(f^k) \quad \forall i, \forall k$$

$$x_{ij}^k (T_i^k + t_{ij} - T_j^k) \leq 0 \quad \forall i, \forall j, \forall k$$

sub route time:

$$a_i \leq T_{n,i}^k \leq b_i - \tau(f_n^k) \quad \forall i, \forall k, \forall n$$

$$y_{ij}^k (T_{n,i}^k + t_{ij} - T_{n,j}^k) \leq 0 \quad \forall i, \forall j, \forall k, \forall n$$

main route loads:

$$D_i^k \leq L_i^k \leq Q^k \quad \forall i, \forall k$$

$$x_{ij}^k (L_i^k + D_j^k - L_j^k) \leq 0 \quad \forall i, \forall j, \forall k$$

$$x_{in}^k (L_i^k + \sum_i \sum_j \sum_l D_i^l y_{n,ij}^l - L_n^k) \leq 0 \quad \forall i, \forall k, \forall n$$

sub route loads:

$$D_i^k \leq L_{n,i}^k \leq Q^k \quad \forall i, \forall k, \forall n$$

$$y_{ij}^k (L_{n,i}^k + D_j^k - L_{n,j}^k) \leq 0 \quad \forall i, \forall j, \forall k, \forall n$$

Figure 2.18: The cross-docking CFR problem mathematical formulation

In this formulation, the indices are *i*, *j*, *k*, *l*, *n*, and *o*. As before, the index *i* and index *j* refer to the nodes in the graph. The index *k* and index *l* refer to the routes in the graph. The index *n* refers to the cross-docking facility. The index *o* refers to the origin and the final destination of the route, which can be the plant or a cross-docking facility.

The parameters of CFR/CDR are listed in Table 2.12 below:

Table 2.12: The parameters of cross-docking common frequency routing problem

Symbols	Descriptions
a_i	The start of service time of node i.
b_i	The end of service time of node i.
c_{ij}	The cost of traveling, usually proportional to the distance between nodes i and j.
t_{ij}	The travel time between nodes i and j.
D^k_i	The quantity of load to pickup at or delivery to node i by route k.
Q^k	The transportation capacity limit of a route, normally due to the size of a trailer.
β_i	The coefficients for the space or inventory cost (of node i) in the objective function.
γ	The amount of space, or effectively, inventory, allocated to the entire system.
γ_n	The amount of space allocated to the cross-docking facility n.

The variables of CFR/CDR are listed below:

Table 2.13: The variables of cross-docking common frequency routing problem

Symbols	Descriptions
x^k_{ij}	A binary equal to one if node i connects to node j in route k and zero otherwise. The x^k_{ij} define the routes by identifying the connections i,j that the route follows.
$y^k_{n,ij}$	A similar binary that applies to the cross-docking facility n.

Table 2.13 (continued)

$T^k{}_i$	The time when route k reaches node i.
$T^k{}_{n,i}$	The time when route k reaches node i in cross-docking facility n.
$L^k{}_i$	The cumulative space reserved for the load when the vehicle traversing route k arrives at node i.
$L^k{}_{n,i}$	A similar cumulative space that applies to the cross-docking facility n.
f^k	The number of pickups performs by route k.
$f^k{}_n$	The number of pickups performs by route k for cross-docking facility n.

The inequalities and their detail descriptions for the CFR/CDR are listed below:

Table 2.14: The inequalities of cross-docking common frequency routing problem

Inequalities	Descriptions
$\sum_j \sum_k x_{ij}^k + \sum_j \sum_k \sum_n y_{n,ij}^k \geq 1 \quad \forall i$	At least one main route or one sub route leaves a node.
$\sum_k \sum_i x_{in}^k f^k \leq f_n^k \quad \forall k$	The frequency of the sub route is at least the frequency of the main route that visits the cross dock of the sub route.
$\sum_i x_{ij}^k - \sum_i x_{ji}^k = 0 \quad \forall j, \forall k$ $\sum_i y_{n,ij}^k - \sum_i y_{n,ji}^k = 0 \quad \forall j, \forall k, \forall n$	In every route, the number of arrivals and the number of departures at a node are equal.
$\sum_i x_{io}^k = 1 \quad \forall k$ $\sum_i y_{n,io}^k = 1 \quad \forall k, \forall n$	All routes return to the origin or the plant.

Table 2.14 (continued)

$\sum_{i} x_{oi}^{k} = 1 \quad \forall k$ $\sum_{i} y_{n,oi}^{k} = 1 \quad \forall k, \forall n$	All routes leave the origin or the plant.
$\sum_{i}\sum_{j}\sum_{k} D_i^k x_{ij}^k \le \gamma$ $\sum_{i}\sum_{j}\sum_{k} D_i^k y_{n,ij}^k \le \gamma_n \quad \forall n$	The interval at which the load is pickup uses less than or equal to the space allocated for the plant and for the cross-docking facilities.
$\sum_{i}\sum_{j}\sum_{k} D_i^k x_{ij}^k + \sum_{i}\sum_{j}\sum_{k}\sum_{n} D_i^k y_{n,ij}^k \le \gamma$	An alternative to the two inequalities above that allocates space in aggregate across the crossdocks and main plant.
$a_i \le T_i^k \le b_i - \tau(f^k) \quad \forall i, \forall k$ $a_i \le T_{n,i}^k \le b_i - \tau(f_n^k) \quad \forall i, \forall k, \forall n$	A route visits a node during its service time, including all subsequent pickups.
$x_{ij}^k (T_i^k + t_{ij} - T_j^k) \le 0 \quad \forall i, \forall j, \forall k$ $y_{ij}^k (T_{n,i}^k + t_{ij} - T_{n,j}^k) \le 0 \quad \forall i, \forall j, \forall k, \forall n$	If there is a travel between a pair of nodes, the different in time between the arrival at the next node and the departure at the previous node is the traveling time.
$D_i^k \le L_i^k \le Q^k \quad \forall i, \forall k$ $D_i^k \le L_{n,i}^k \le Q^k \quad \forall i, \forall k, \forall n$	The space allocated so far in the route is more than or equal to the load it picks up, but less than or equal to the capacity of the route.
$x_{ij}^k (L_i^k + D_j^k - L_j^k) \le 0 \quad \forall i, \forall j, \forall k$ $y_{ij}^k (L_{n,i}^k + D_j^k - L_{n,j}^k) \le 0 \quad \forall i, \forall j, \forall k, \forall n$	If there is a travel between a pair of nodes, the different in aggregate space allocated between the current node and the previous node is the load it picks up at the current node.

Table 2.14 (continued)

$x_{in}^{k}(L_i^k + \sum_i \sum_j \sum_l D_i^l y_{n,ij}^l - L_n^k) \le 0 \quad \forall i, \forall k, \forall n$	If there is a travel from a supplier to a cross-docking facility, the different in aggregate space allocated for the supplier and that for the cross-docking facility is the sum of all loads the facility is picking up by its routes.

2.3.2 Methodology

For solution of this model, we extend the CFR taboo search algorithm to CDR. The procedure that generates the initial solution does not change. The neighborhood search is modified to include sub-routes. The cross-exchange search can consider moving any part source to the sub-routes if the move is favorable.

Calculating the load is a bit trickier in CDR. When there is an exchange of part sources between a main route and a sub route, or two sub routes of different cross-docking facilities, the total pickup load at each cross-docking facility requires an update. In our implementation, we allow such an exchange, but penalize it (by a constant factor times the amount over the vehicle capacity) if it makes the solution infeasible.

The procedure for calculating the visiting time for main routes remains the same. The procedure for the sub routes moves the origin from the plant to the cross-docking facility. The process only affects the first and the last distances of the route and the visiting time of each pickup.

The space constraints for the main routes do not change. Note that the amount of load picked up on the sub routes does not affect the total space of the main routes. The only factor that changes the total space of the main routes is the pickup frequencies of all the main routes. The space constraints for the sub routes are similar to the space constraints for the main routes. The total space of the sub-routes also depends on the pickup frequencies of the sub-routes only.

2.3.3 Results

The CDR algorithm is implemented with a Microsoft Visual C/C++ Compiler on an Intel Pentium III 450Mhz computer running the Microsoft Windows XP Professional operating system. The program is object-oriented and complies with the ANSI C++ standard. It also compiles under GNU g++ with the University of Kentucky's HP Superdome supercomputer.

For the sake of comparison, we use the same basic problem to test the CDR algorithm as used in the GFR and CFR comparison in Section 2.1.10. Table 2.4 gives the input parameters of the problem. From that problem, we add a cross-dock facility at $(X, Y) = (25, 88)$.

First, in our cross-dock formulation, we require that the sub routes' pickup frequency be equal to or greater than their respective cross-docking facilities' frequencies. The justification is that without this constraint, the algorithm can easily circumvent the space constraints. To illustrate, we simulate the algorithm without the sub route frequency restriction, and the solution of the problem with $\gamma=27$, $\gamma_I=27$, is shown in Table 2.15 below.

Figure 2.19 below shows the graph of the CDR solution. The green triangle represents the cross-dock facility; the pink square represents the plant.

Obviously, it is definitely better that the sub route (the green and round dotted route) becomes the main route, as the travel distance is shorter. But, running this route as a main route requires more frequent pickups at the suppliers. Specifically, as a sub route, it can run at a frequency of one. As a main route, it will run at a frequency of three to satisfy the main routes' space constraint. Thus, our carefully constructed space constraint is circumvented.

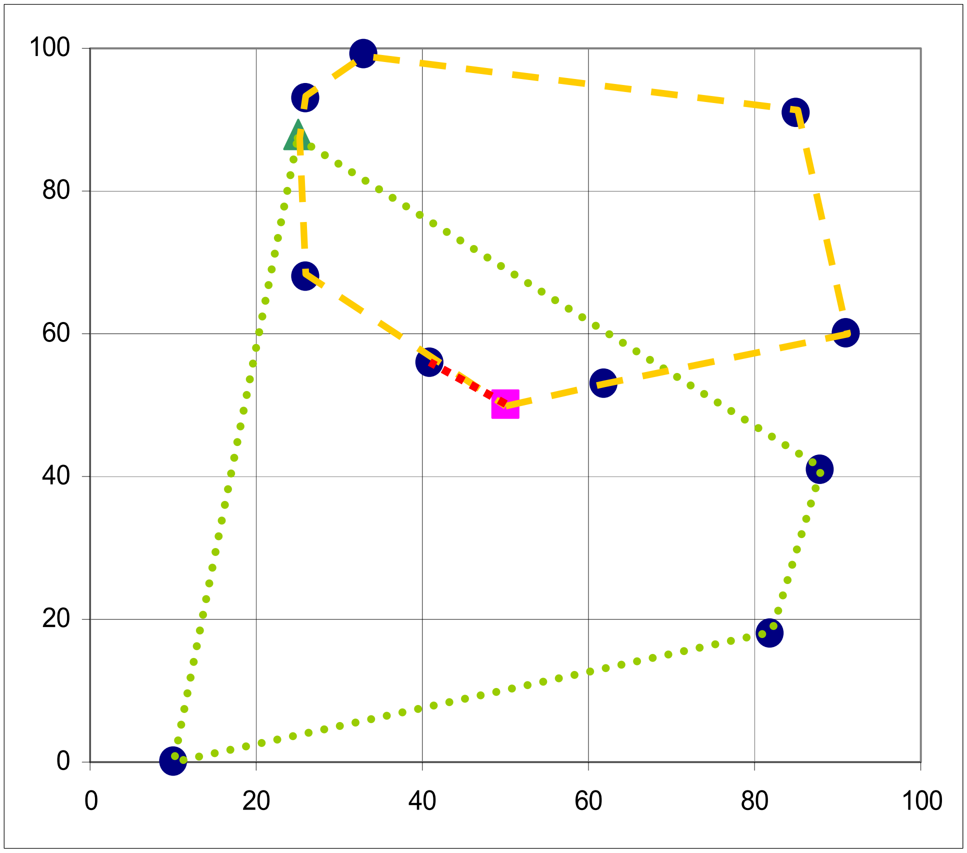


Figure 2.19: The CDR Solution of a Random Generated Problem at $\gamma = 27$

To overcome this problem, we require that the sub routes run at the minimum the frequency of their respective cross-docking facilities, as represented by the second cross-dock flow equation in Figure 2.10. There are other ways to handle this problem, such as adjusting the sub routes' space constraints or designating a priori the cross-dock suppliers. Note that there is nothing wrong with the solution in Table 2.15, except that the extra cost spent for improving the pickup frequencies is wasted.

Table 2.15: The CDR Solution of a Random Generated Problem at $\gamma = 27$

TABU SEARCH	
COST: 946.22 GAMMA 0: 26.8667 GAMMA 1: 25	VEHICLES: 3 TIME: 26.719 S
FREQ: 3 MAIN ROUTE: 0-11-5-10-2-9-1-4-0	FREQ: 5 MAIN ROUTE: 0-8-0
FREQ: 1 SUB ROUTE: 1-6-3-7-1	

After adding the extra cross-dock frequency constraint, the new optimum solution is the solution in Table 2.6. In order words, the cross-docking facility is not needed in this problem. Cross-docking facility is only useful in extending the suppliers' time windows. The time windows in the current problem are not critical. Even if time window is critical, solutions using cross-dock facilities are never better than the normal solutions, as cross-docking facilities just add to the travel distances. A simple example would be to have a number of suppliers that the main plant cannot reach. But in such a case, it is easier to solve the problem in two.

2.4 Summary

In this chapter, we have presented three routing problems and their respective mathematical formulations, GFR, CDR, and CFR, and three algorithms to solve these problems. The major contribution in this chapter is in successfully applying heuristic methods to three new but practical routing problems. These problems consider two important features of JSS: the requirement to have limited storage space in a JIT environment and the requirement to replenish parts in small quantities with heijunka delivery.

Chapter Three: JSS Systems Characteristics and Their Effects on the Costs of Common Frequency Routing

In this chapter, seven structural characteristics are explored to determine their effects on the economics of a Just-in-time Supply Pickup and Delivery System (JSS) using the CFR route optimization procedure.

3.1 Overview

Just-in-time (JIT) systems practice heijunka in parts supply, i.e. frequent deliveries of parts in small quantities. The advantages of such a strategy include:

a. Low work in process (WIP) levels and holding costs for parts and materials.

b. Reduced material handling requirements in situations where direct delivery of the parts to point-of-use is possible without intermediate storage or staging.

c. Greater flexibility and more rapid response to market events such as the need for engineering changes and demand shifts.

d. Tight control over supplier performance in terms of both delivery and quality.

e. In general, because of low buffer stocks, maintenance of a healthy stress on the system necessary to provide early warning of problems and motivation for improvement.

Although the magnitude of economic benefits of c, d and e above are, a priori, difficult to quantify, experience at successful lean manufacturing plants have shown them to be substantial.

Given a particular demand for parts, clearly the least expensive means of transporting these parts would be to employ full vehicles making infrequent deliveries of large quantities of parts from single suppliers. In contrast to this approach, JSS strategy deploys vehicles to carry a variety of parts and materials from a number of suppliers in low quantities. Because of transporting small quantities of parts and materials, a route must run frequently to meet the demands of the plant. Moreover, assuming level scheduling of the plant, the vehicles should deliver these parts at evenly spaced intervals to synchronize supply with demand and enable operation with small parts buffers. Naturally, large JIT plants that have more suppliers have more flexibility in design of efficient routes that do not add excessive costs relative to large quantity/low frequency delivery systems. Nonetheless, external transportation costs are higher under this philosophy and it is appropriate to assess the tradeoff between these costs and the ensuing benefits.

Recent studies by Chuah (2000) and Chuah and Yingling (in press) have addressed the issue of optimization-based routing for JSS. The approach, discussed in more detail below, has much in common with traditional optimization-based routing problems that determine minimum cost routings that service a network with defined transportation demands between suppliers and customers. A unique feature of our approach is that it defines not only routes but also the frequency that these routes are run. Moreover, these frequencies must be high enough so that the overall inventory level satisfies a predefined inventory cap. This cap might be expressed in terms of maximum space available for storage of in hours of inventory. In summary we have established a procedure that

1. automates the JIT route design process and runs very quickly,
2. defines (approximate) minimum costs routes, and
3. is parameterized by the inventory cap that the JIT firm wishes to operate.

For a given situation – in terms of parts demands, supplier locations with respect to the manufacturer, transportation fleet characteristics, and pickup time windows – we use the model in this chapter empirically to establish how total transportation costs vary as a function of the magnitude of this inventory cap. This relationship provides a basis for analysis of the tradeoff between inventory and transportation costs and provides valuable information for defining an appropriate inventory cap on supplied parts for a given plant.

In the next section, we describe the model formulation for CFR in more detail. The section is followed by a numerical study of alternative transportation scenarios that gives us insights the nature of the cost/inventory relationships for milk-run delivery systems. Next, we develop a procedure for estimating the number of hours of inventory for a given plant that appropriately reconciles the tradeoff between transportation and internal costs associated with inventory level.

3.2 Common Frequency Routing

A detailed mathematical formulation of our model along with a discussion of numerical solution strategies can be found in Chuah and Yingling (in press). Our purpose here is to describe the capabilities and features of this JIT routing design approach clearly.

The model solution determines:

- The suppliers a particular route visits
- The frequency that the route is operated, i.e., the number of times a supplier is visited per day
- The trailer size (e.g. 48 or 52 feet) assigned to that route
- The schedule for visiting each supplier on the route
- The specific parts picked up at each supplier on the route. Note that not all parts produced by a particular supplier need to be picked up on a given route visiting that supplier.

However, all of the volume for a given part is assign to a single route. The routes designed in the course of the solution of the model satisfy the following major constraints:

- Time windows are honored for each supplier visited on a particular common frequency route.
- Truck capacity (48 or 52 feet) is not exceeded and both pallet and rack rounding factors are precisely accounted for in the formulation as a function of the frequency that a given route is run.
- The inventory of parts allowed in the JIT plant is capped at a particular level. Note that as this cap is lowered, this constraint forces solutions that employ higher frequency routes, imposing greater demand for heijunka on the parts delivery system. Currently this cap is on the aggregate inventory level, allowing parts with high transportation costs to be delivered with lower frequency relative to parts with low transportation costs.

In solving the model, our search procedures identify low cost routes that satisfy these constraints. The key determinant of cost is the time and distance requirements for traversing a given route and this cost is multiplied by the frequency that the route is run. Other costs can also be readily accounted including the inventory holding costs and penalties for route designs that require the vehicle to unload at multiple receiving docks at the JIT plant.

Our preferred solution strategy is based on tabu search approaches. We have developed approaches that can handle realistic scale problems and the solutions we establish appear to be near optimal.

In our model, each route is only permitted to run at one frequency. We call this common frequency routing (CFR). CFR is recognized by JIT suppliers such as Toyota to produce routes that are simple and easier to manage especially in scheduling trailer unloading at the plant. The use of CFR also simplifies solution of the model by reducing the dimensionality of the search. However, it is possible as shown in Chapter 2 to relax this constraint in route design and perhaps discover lower cost routes. Based on manual design experiments comparing CFR and general frequency routing as well as comparisons to between CFR and GFR as discussed in chapter 2, the cost benefits of general routing seemed to be small.

Also, note that our model, in order to keep computer run-time requirements reasonable, only schedules the timing of the first run of the route not all the runs as defined by the route frequency. For example, if a route is run with a frequency of four, timing is only specified for the first run, but not the remaining three runs. Constraints are used to insure adequate time exists at each supplier on the route to make the additional runs. These runs would have to be scheduled manually. In general, it is a simple offsetting of the run times except when it is necessary to resolve the time conflicts for suppliers served by multiple routes.

We have reported some of the finding discussed below in Chuah and Yingling (2001) (but performed as part of this dissertation) and these results are summarized in Section 3.3. These studies address the effects of the manufacturing plant's location on routing cost, the effects of the length of time windows on routing cost, and the effects of the number of suppliers on routing cost. Moreover, below we add studies that address the effects of supplier clustering on routing cost, the effects of demand variation on routing cost, the effects of vehicle capacity on routing cost, and the effects of load distribution on routing cost and routing frequency.

Figure 3.1 shows a typical cost/inventory relationship from our studies. The curve is obtained by varying the total limit on space (or equivalently inventory) at the plant. For each point on the curve we have generated a solution to a CFR routing problem and the space limit has been plotted against the objective function value which represents transportation cost. As we can see, the cost levels off to a minimum value when the space constraint is very high. In this circumstance, there is no requirement to deliver with heijunka and trucks run infrequent routes to individual suppliers and pick up full loads (the cheapest way to transport parts). As we decrease the space cap, we force the system towards smaller quantity, higher frequency deliveries. From the perspective of the route, multiple suppliers must be visited and longer distances must be traversed adding to transportation costs. This results in an increase in transportation costs as shown on the curve. Note that this increase is gradual at first and then starts rising more steeply as we impose smaller and smaller caps. In addition to forcing longer routes with more suppliers and higher transportation costs, it is important to recognize that there is an additional factor that causes costs to increase with the decreasing caps. As we go to longer routes, the impact of supplier time windows becomes more critical. It becomes more difficult to build routes that meet all the time windows collectively especially routes that run at high frequency (see Figure 2.16). To meet the space cap we force the system to use routes that are spatially inefficient that meet time window feasibility. For this reason, costs tend to rise more abruptly as the space cap gets small.

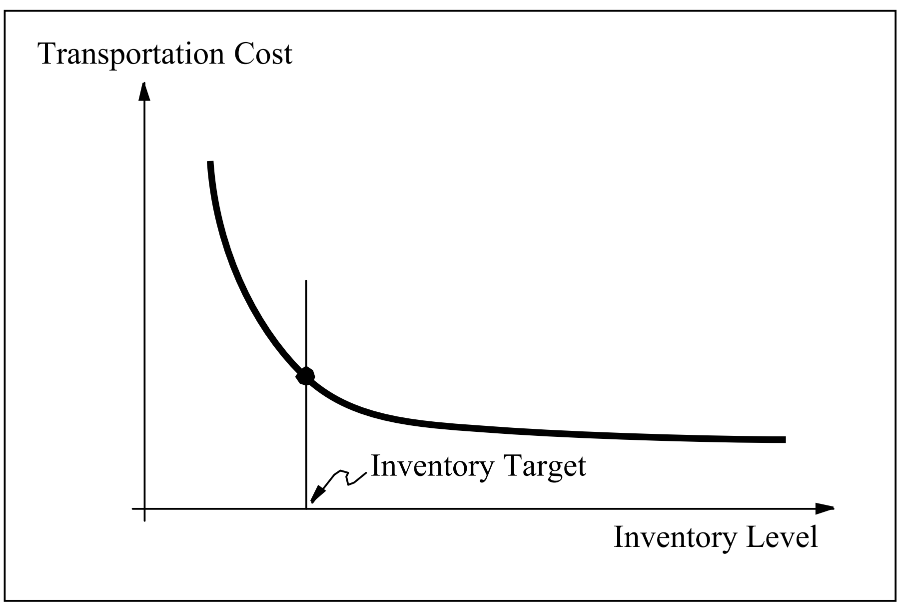


Figure 3.1: A typical cost/inventory relationship

3.3 Case Studies of CFR

We wanted to see how the nature of the inventory/cost relationship depends upon major application characteristics. Table 3.1 shows the cases that were considered. In each of these cases, the spatial location of the suppliers where generated randomly within the prescribed bounds of the field. Minimum costs routes where generated for storage space (inventory) limits as large as 1000 standard pallets down to a minimum of 10 pallets (such solution was not feasible in any of the cases). The results are plotted in figures 1, 2, and 3. Note that in all cases, the inventory holding costs at the plant were very small relative to the transportation costs, as might be appropriate for a high volume JIT supplier with frequent inventory turns. For each point on this curve our model was generating a complete minimum cost routing design.

Table 3.1: The CFR cases that have been tested

Test Cases	Plant Location	Time window start and end	Number of Suppliers
Case 1	Corner	700-800 to 1700-2300	100
Case 2	Center	700-800 to 1700-2300	100
Case 3	Center	800-900 to 1600-1800	100
Case 4	Center	800-900 to 1600-1800	75
Case 5	Center	800-900 to 1600-1800	88

The input characteristics of the cases, where the maximum pickup frequency is 7 per day, the vehicle capacity is 25 pallets, and the volume per supplier is between 10 pallets and 100 pallets per day

The first observation that can be made is that the general shape of the curve is similar in all cases. Transportation costs at first increase only gradually as inventory levels are reduced and then begin to rise exponentially as a lower bound is reached. This general feature is used in Section 4 to aid the specification of appropriate inventory levels for a given plant.

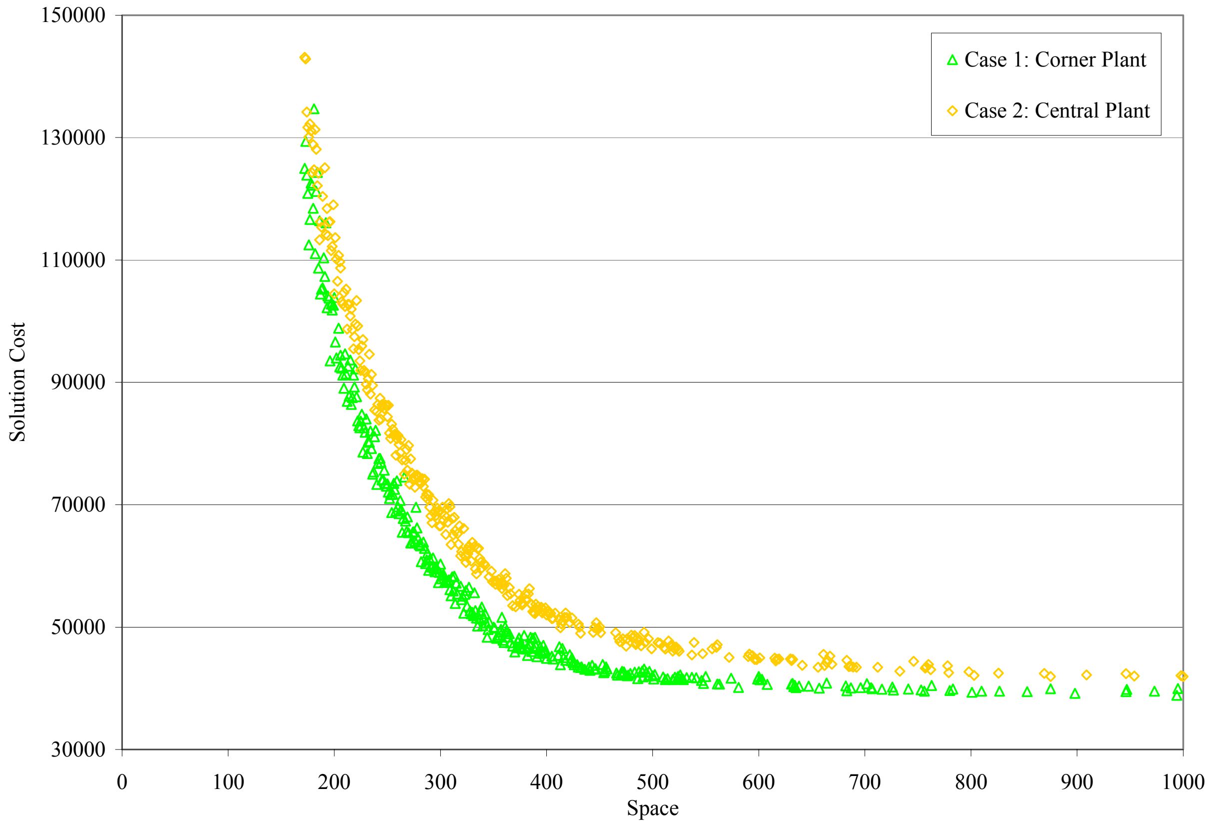


Figure 3.2: The effect on supplier geometry on the cost/inventory relationship

Figure 3.2 shows the effect on supplier geometry on the cost/inventory relationship. In case 1, the JIT plant is located in the corner of the spatial field. Such a situation might exist because of geographic boundaries such as a plant located near an ocean or major lake. In case 2, it is located centrally. Average distance between the suppliers and the plant are the same for both cases. As would be expected, in the case with the corner plant, transportation costs are less because suppliers are more clustered relative to the plant, facilitating route design. Notice that at first as the inventory levels are reduced, costs grow more rapidly for the centrally located plant than they do for the corner plant. The reason for this is that it is easier to design low cost routes for the clustered suppliers in case 1 relative to the more widely distributed suppliers of case 2. However, as the inventory cap reaches very small levels, the cost of solutions tends to move to similar values. A plausible explanation for this is that as the frequency of the routes is forced to be higher, the routes must traverse larger regions and the advantage of supplier clustering in design of these routes diminishes.

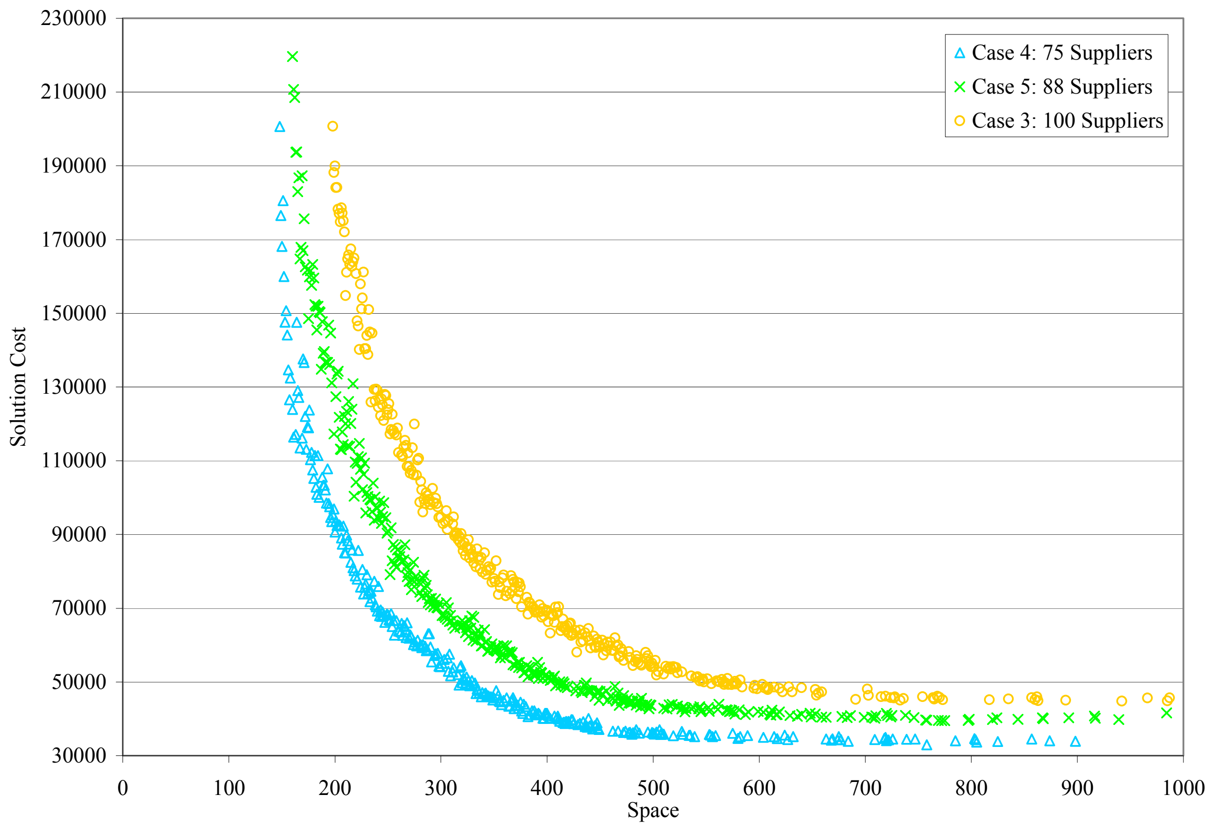


Figure 3.3: The effect of the number of suppliers on the cost/inventory relationship

Figure 3.3 shows the effect of the number of suppliers on the cost/inventory relationship. In cases 3, 4, and 6 these were 100, 75, and 88 suppliers, respectively. The suppliers are randomly distributed over the same spatial region with approximately the same average distance. The total load to be hauled is proportional to the number of suppliers across the three cases as is the total distance traveled. As we expect, the cost is higher as we increase the number of suppliers and the total load. Interestingly, costs rise faster as the inventory cap is reduced for plants with larger number of suppliers and higher volume to transport.

Figure 3.4 illustrates the effect of supplier time window on the cost/inventory relationship. In case 2 the time windows are relaxed. In case 3 they are tight. The effect of tightening time windows on costs is quite dramatic. As the windows are restricted, the costs rise very fast as higher frequency routes are sought. This is probably due to the difficulties in scheduling high frequency routes under tight time window constraints. The graph illustrates that negotiating broad time windows with suppliers is important for running the JIT plant with low inventories and low transportation costs.

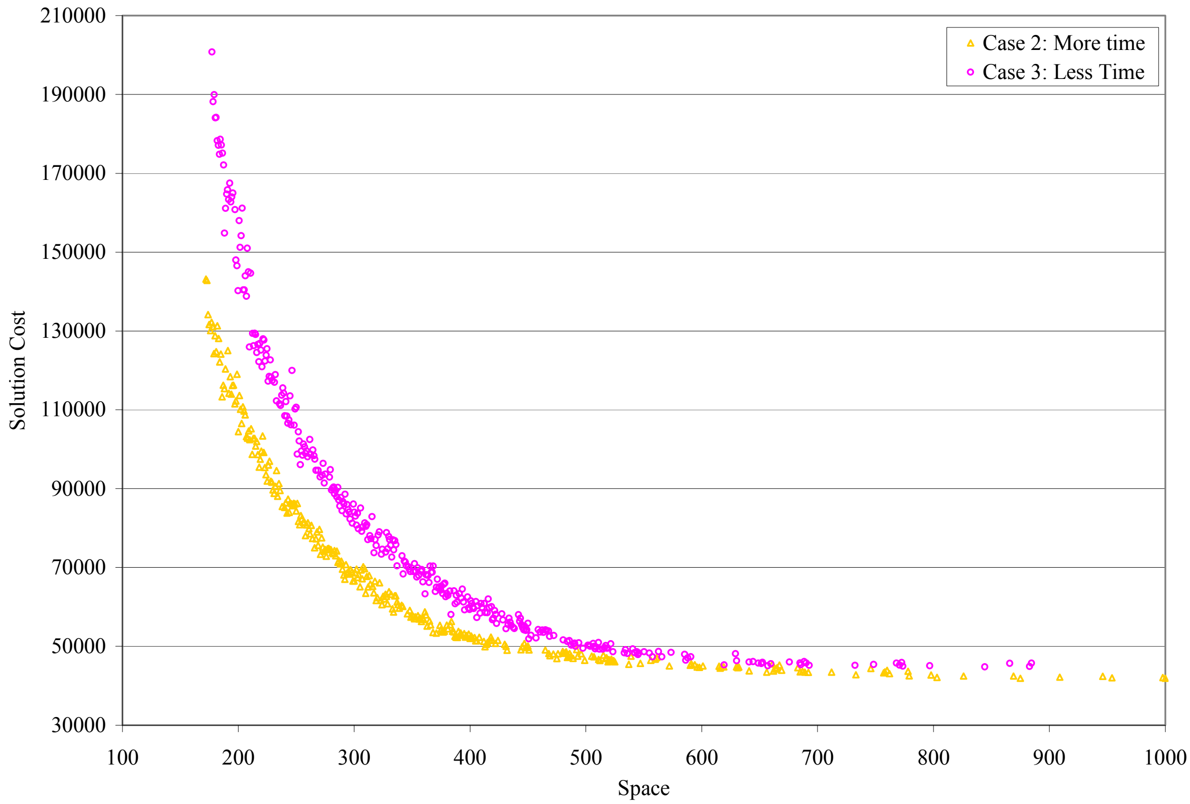


Figure 3.4: The effect of supplier time window on the cost/inventory relationship

3.4 Suppliers Clustering

In the earlier study, we look at supplier geometry based on the plant location. It is found that when suppliers are clustered, the routes become more efficient. In this study, the scenario is that the supplier is actually clustered at a local area. Figure 3.5 shows a plot of the solution costs of two randomly generation problems with 50 suppliers against the storage space of the system. In the first problem (R8), the suppliers are randomly placed in a 1000 by 1000 grid. In the second problem (R8-C), the suppliers are clustered in the up-right square of the grid and the lower-left square of the grid. In both problems, the plant is located at the center (500,500). Note that by this design we have much higher clustering in the second problem than in the first but the average distance to a supplier is essentially the same for both problems. The input files and parameters of these problems are shown in Appendix C.

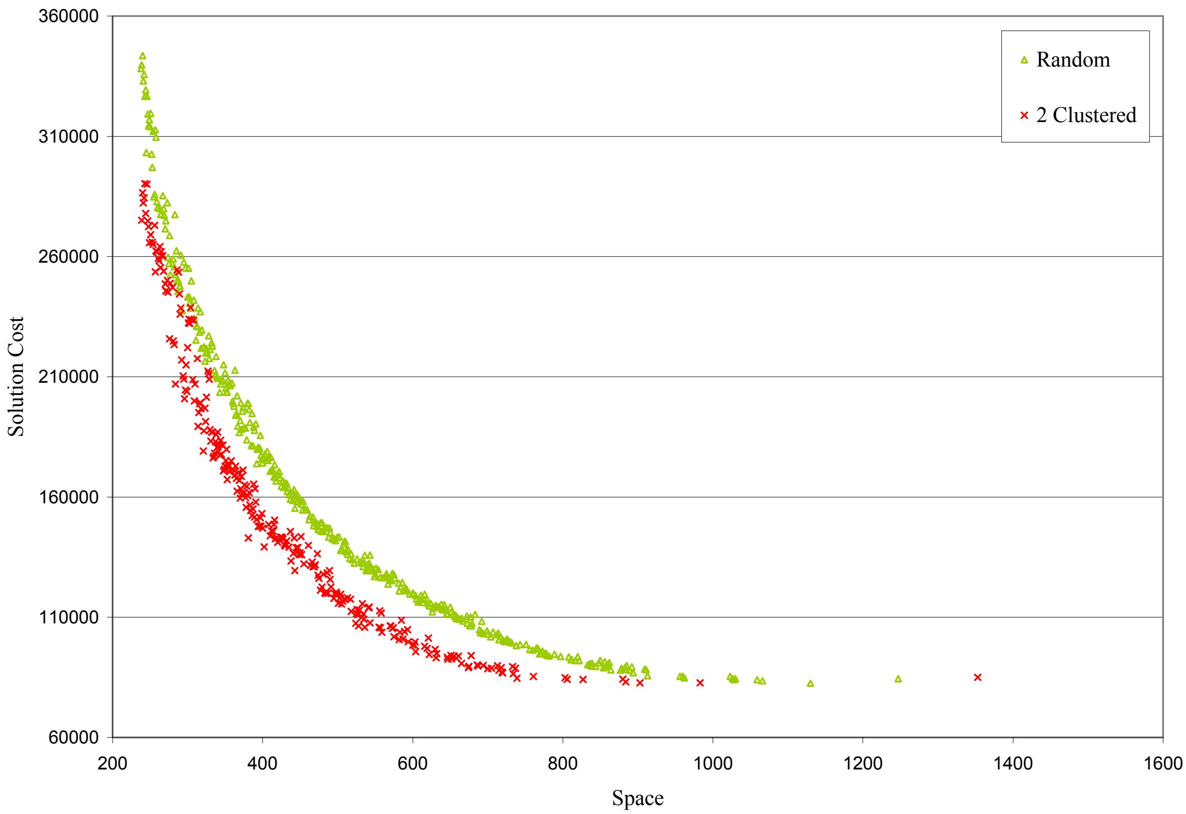


Figure 3.5: Solution Cost of CFR Problems with 50 suppliers and clustering effect

Each green triangle in the graph above is a solution of R8 with a different storage space limit, γ (represented as gamma in the formulations). The red squares are solutions of R8-C. The graph shows that for a relaxed constraint on space or inventory the effect of clustering is null. This is not surprising since, under the relaxed conditions, routes will visit a small number of suppliers infrequently to save on transportation distance. Since the distance to the suppliers is the same for both cases, there is no significant difference in costs. As the space constraint tightens, the clustering effect increases with a significant reduction in cost of transportation for a clustered system over a non-clustered system. Clustering makes it easier to design routes that, by the restrictive space limit must serve a significant number of suppliers, with low transportation distance. For this particular problem at some point around γ=*300*, the solution costs of R8-C suddenly jump. This is because the cost change is very steep when the storage space is small. It is harder for the algorithm to climb out of local optimum points and such jumps in the curve are common. The steep pricing increase and the closure of the gap between the clustered and non-clustered curves also indicate that the clustering effect is waning at very high frequency. Most of routes reach the maximum frequency of 12 at that point. This is readily explained by the fact that when the space constraint forces very high frequency, long routes must be run that visit a large number of suppliers and clustering offers less of an advantage than it did when shorter routes could be employed to visit a smaller number of suppliers. In summary, we gain from clustering, but only at mid-level frequencies, not very high or very low frequencies. Furthermore when the graph is compared to the cases in the earlier study, the price differences at low frequency has been eliminated.

3.4 Demand Variation

During planning, JSS may experience a sudden increase or decrease in the production volumes. These scenarios are possible because the pickup volumes in JSS are based on forecast values instead of firm orders. Figure 3.6 below shows the differences in the solution costs if the pickup volumes were increased by +/- 20 percent. The problem is R10 and the input files and parameters are shown in Appendix C.

As expected, an increase or decrease in production volumes creates a uniform shift of the solutions' curve. For the normal load, the solutions are a bit more disperse due to a set of weaker termination conditions. JSS systems are normally designed with significant safety factors (e.g., 8-10%) to accommodate for deviations above forecast. This comparison shows that the cost of such safety factors is quite substantial.

Interestingly, the gap between the –20% and normal curve and the normal curve and +20% is nearly the same at low frequency solutions that occur under a relaxed (large) space limit. As we tighten the space constraint and increase route frequency, the gap between the –20% case and the normal curve is much greater than the gap between the normal curve and the +20% case. This implies that under conditions of tight space constraints where higher frequency routes are required, the higher the volume requirements, the less the penalty for increased volume requirements. This makes sense because much of the increased volume can be accommodated by filling empty space on high frequency routes without adding a lot of miles.

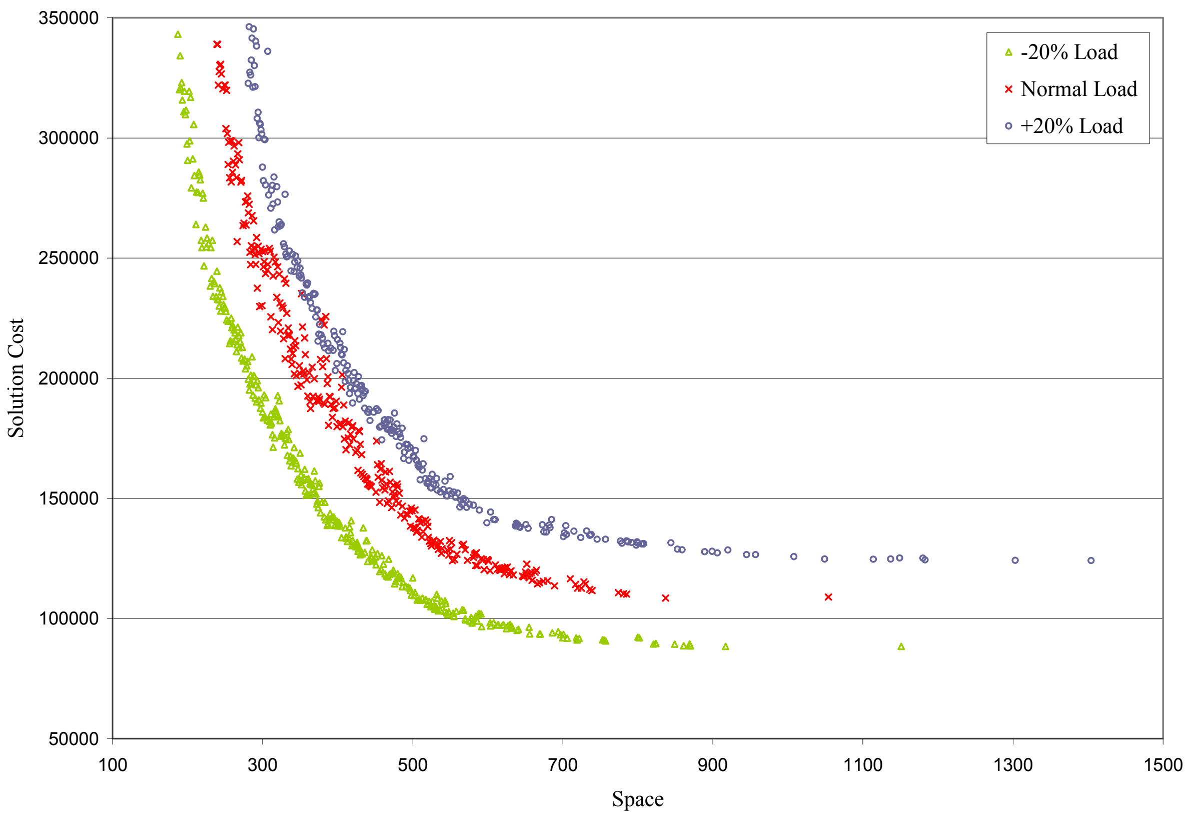


Figure 3.6: Solution Cost of CFR Problems with 50 suppliers and different pickup loads

3.5 Vehicle Capacity

Figure 3.7 below shows the differences in the solution costs if the vehicle capacity were changed. The problems are R6, R8, and R11, respectively, and the input files and parameters are shown in Appendix C.

First of all, the difference between the two curves on the right side illustrates the impact of economies of scale in the transportation vehicle in running a traditional logistics system. Note however, that the cost difference between 30 and 55 is much greater than the difference between 55 and 80 even though the capacity differences are equal. This indicates that the economies of scale diminish as we go to larger and large capacity vehicles. The critical thing is not to employ too small of a vehicle.

In the graph, note that the bend of the solution curve for the problem with the smallest vehicle capacity is quite sudden and sharp. In this problem, the solutions are time constrained at high frequency and low space conditions. At some point around *γ=400*, the solutions switch to vehicle capacity constrained. For the problem with a vehicle capacity of 80, the solution curve is always time constrained. Importantly, this graph shows that vehicle capacity is less important when the space cap is low and high frequency routes are necessary. This indicates that there is likely little advantage in transportation cost to using 52 foot over 48 foot trailers or tandem trailers over single trailers in JSS systems.

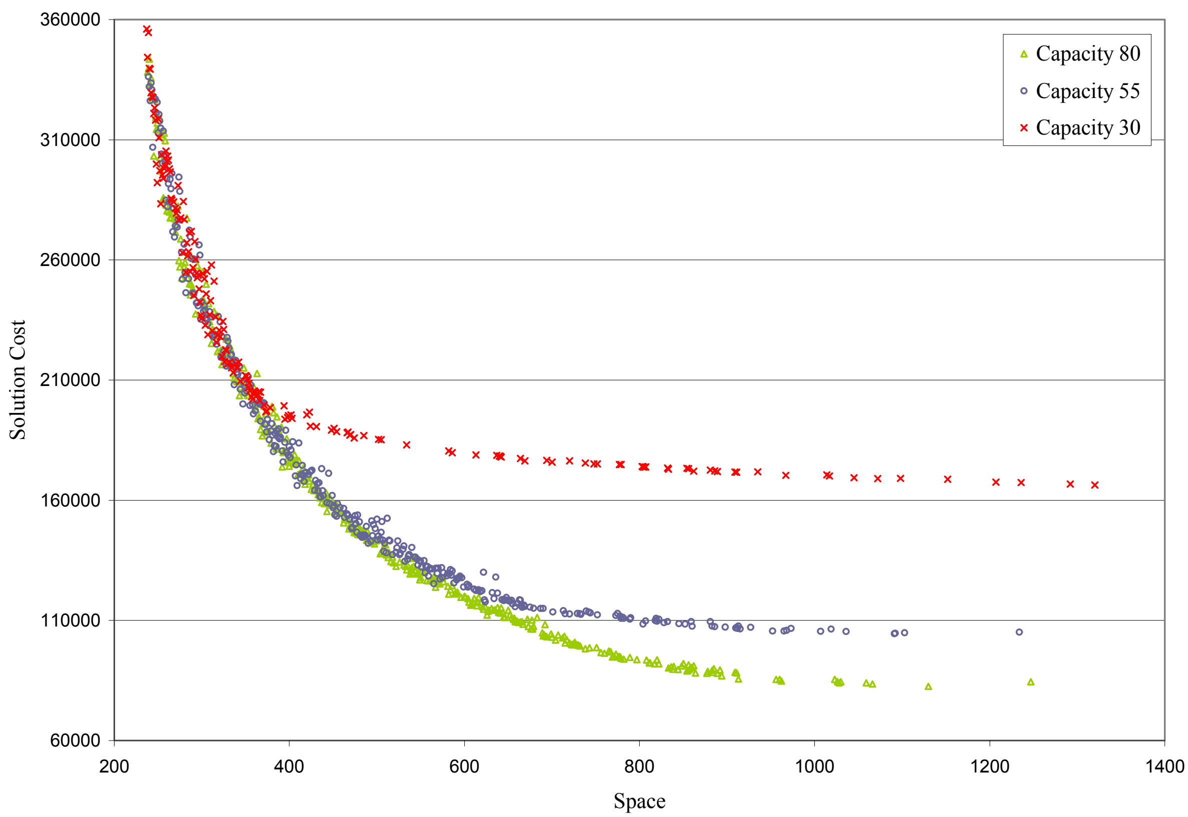


Figure 3.7: Solution Cost of CFR Problems with 50 suppliers and different vehicle capacity

3.6 Load Distribution

Figure 3.8 below shows the differences in the solution costs if the suppliers load distributions were changed. The problems are R1, R2, and R3, respectively, and the input files and parameters are shown in Appendix C.

One might have thought that narrow distributions in transportation loads would benefit the system because similar pickup frequencies could be used for all suppliers. However, interestingly, load distributions are not important factors in common frequency as long as the average loads remain the same. The system can adjust to widely varying loads without adding cost.

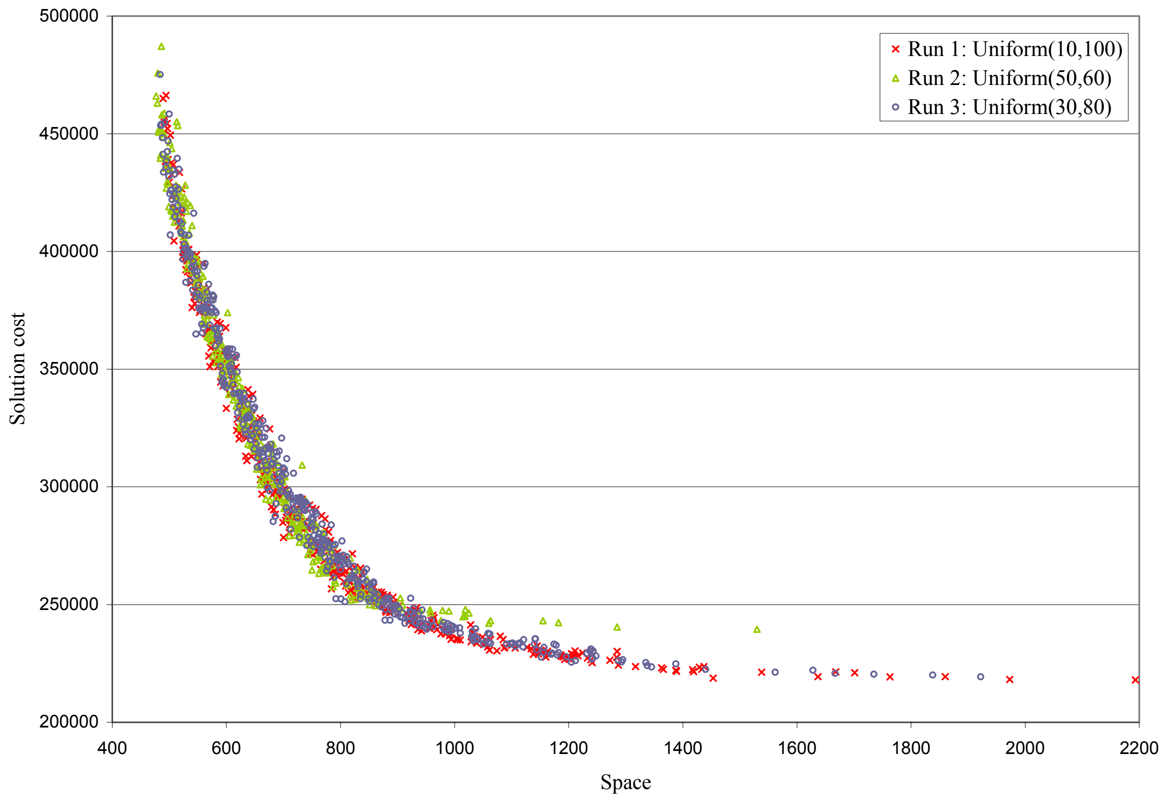


Figure 3.8: Solution Cost of 100-supplier Problems with Different Load Distributions

Figure 3.9 below shows the differences in the average pickup frequency if the suppliers load distributions were changed. Again, there are no significant different in average pickup frequency for the three problems.

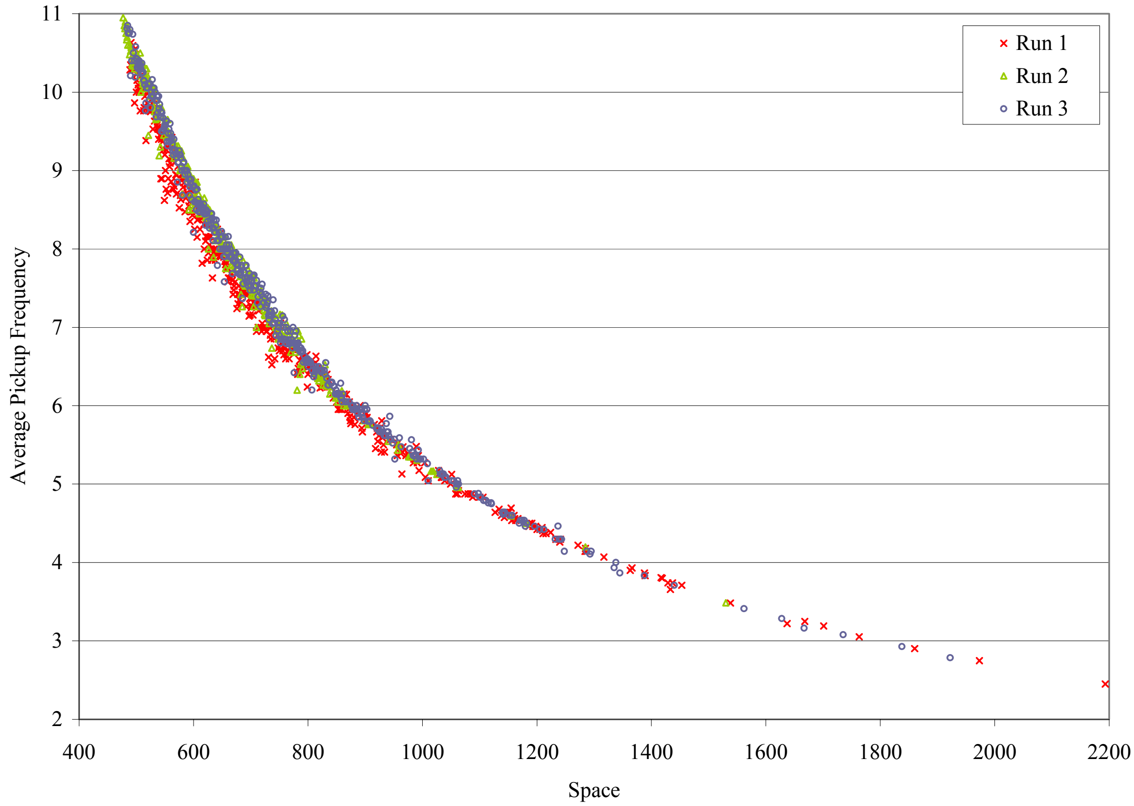


Figure 3.9: Average Frequency of 50-supplier Problems with Different Load Distributions

3.7 Summary

We have looked at the various effects JSS system characteristics on the costs of CFR. Understanding these effects give us insights of CFR routing behaviors and help us becomes more efficient in structuring JSS systems for low cost route designs.

In summary, here are our findings:

- When suppliers are clustered, the routes become more efficient, especially at mid-level frequencies. Clustering is less important at very high frequencies.
- The number of suppliers and the total load are also important. The cost increases as we increase the number of suppliers and the total load.
- Negotiating broad time windows with suppliers is another essential factor for running the JIT plant with low inventories and low transportation costs.

- Similar results are obtained if we form clusters of suppliers around the plant. We gain from clustering, but only at mid-level frequencies, not very high or very low frequencies.
- An increase or decrease in production volumes creates a uniform shift of the solutions' curve. If the volume increase were due to safety factors, the cost of safety factors is quite substantial.
- Vehicle capacity is less important when the space cap is low and high frequency routes are necessary. At high frequency, it makes no difference in increasing the size of the trailers.
- Load distributions (i.e., differences in volumes of parts to be transported across the suppliers) are not important factors in common frequency as long as the average loads remain the same. The system can adjust to widely varying loads without adding cost.

Chapter Four: Simulations of Inventory Dynamics for Just-in-time Supply Pickup and Delivery Systems

In general, simulation modeling is used to analyze a complex system's performance when analytical approaches are insufficient to represent essential detail while full-scale experimentation with a real system is too expensive. In this chapter, we will apply simulation to the study of Just-in-time Supply Pickup and Delivery Systems (JSS) as such systems were defined in chapter one.

The objective of these simulations is to study the stability of JSS in managing inventory supply when such as system is operated under the control of the supplier kanban system. The route planning process controls neither the kanban system, nor the part reordering, nor the supplier selection. But the planning process indirectly affects the later operations. In route planning, all parts are scheduled in the JSS based on forecast of the total vehicle order (TVO) and the current inventory level. On the other hand, the actual production is based on kanban that automatically caps the system's inventory over a planning cycle. Hence, in operation, the route design is static, based on a long term forecast of demand, but the demands that govern the actual loading on the routes are dynamic. As such, short-term policies used in the system to maintain parts supply are important. An unbalanced policy can fill all the trailers with full loads, but still stock-out the inventory at the consumption point. In the case of stock-out, the system will halt the production, as JSS has no provision for a standby safety stock (although some degree of excess stock would be employed in the pipeline to cover contingencies). A simulation study will be able to identify these flaws in short term performance of JSS and assist in finding good policies to overcome them.

Furthermore, one of benefits of JSS is being able to make frequent deliveries in small quantities. Toyota's management constantly stresses the importance of make-to-order and fast delivery to customer. Their decision (Bolte, 2001) to reduce the customer's order-to-delivery lead-time substantially over the next two years will put even more stress on the system, as it will be harder for JSS that employs a static route design over a long duration planning cycle to be responsive changes in demand. Given that Toyota's policy towards continuous improvement, a simulation study can provide a general guideline for possible changes and improvements they might wish to make in order to improve order-to-delivery lead time.

4.1 Literature Review

There are several simulation studies in the literature that focus on the JIT production systems (e.g., Baykoc and Erol, 1998; Lummus, 1995; Savsar and Al-Jawini, 1995). The current research in supply delivery system emphasizes supply chain integration and JIT purchasing (See literature review in Section 1.2). Nevertheless, new literature in inventory control (Kim and Ha, 2003) frequently refers to JIT small lot ordering but ignores the logistics part of the system, such as JSS. It is not surprising because most companies do not directly manage their supply inbound logistics, but instead relegate the problem to logistics companies.

JSS operates under the Toyota Production System (TPS) and hence other simulation studies that discuss this system are relevant to our problem. Hauser simulates the lane sequencing, storage, and dispatching operations at the staging area (written as cross-docking area in the paper) of TPS (Hauser, 2002). The simulation model identifies the best layout for sorting cross-docking pallets and non cross-docking pallets according to lane. These operations occur right after the docking operations of JSS.

In another simulation for TPS, Nagane develops a model to level the vehicle-make sequence at a multilane selectivity bank between the paint shop and the assembly area (Nagane, 2002). The paint shop operation disturbs the heijunka sequence of vehicles. The selectivity bank reorders the sequence before they leave the bank for assembly operations. The simulation model is used to find the optimum buffer size of the selectivity bank. This is the first study that addresses the inventory dynamics in JSS.

4.2 Structure of the JSS Model

This section explains the structure of the simulation model. The basic requirement of the simulation is that we need to model part flow from the part sources through JSS to the consumption points. The part sources come from the suppliers; the consumption points are the production lines inside the plant. Between the suppliers and the plant are the routes that create considerable delays in transportation, delays in the receiving yards at the JIT plants, and delays in the shipping and receiving docks. While the parts flow from the suppliers to the plant, at the same time, the parts ordering information flows from the plant to the suppliers. The timing of this information flow with respect to the pickup and delivery system impacts the actual timing of parts arrival at the consumption points in the plant

Although JSS is a logistic problem, the system derives its controls from the production system. It is a model from a manufacturing system's perspective. To properly simulate the system, we explore a general model before splitting the system into components for analysis. JSS behaves like a lean manufacturing system that tries to establish a good production flow between the suppliers and the plant.

A general manufacturing model is described, as shown in Figure 4.1 below. The system consists of components, people and machines that make useful products. The system is managed across boundaries and interfaces. The boundaries define the scope of the system or subsystem, while the interfaces control the flows through transactions.

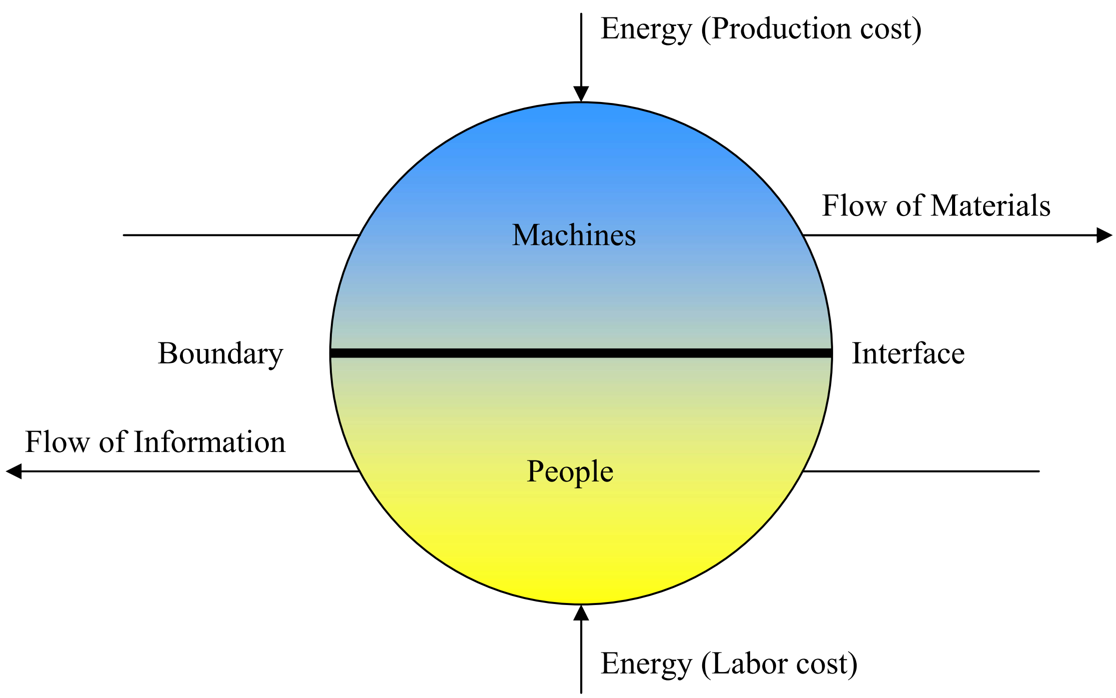


Figure 4.1: A Manufacturing System Model

There are three flows in the manufacturing model: the flow of materials, the flow of information, and the flow of cost. These flows establish the value streams. Components of the value stream can be value-add or waste, depending on the operating conditions. For example, excess material flows become a stream of inventories, while excess information leads to confusion in process execution. By managing the flows, we can control the streams. An effective control of these streams is required for lean production.

As mentioned earlier, the interfaces control the flow. For example a conveyor regulates the flow of materials and a visual control regulates the flow of information between two stations. The interfaces arise from disconnected points in the system, e.g., the physical distances between two machines, the communication barriers between two people, or the control panels between a machine and an operator. It is often a good location for cost transactions. As the number of components and interfaces grows, the machines become factories and the people become organizations.

In the JSS model, the parts represent the materials, while the kanban represent the information mechanism. In this way, we can analyze the efficiency of these flows. Associated with each device that handles the parts or kanban, a cost is applied to the operation of the device. Therefore a build up of parts and kanban implies an increasing cost. The model has two important interfaces between three major components: the suppliers, the carrier, and the manufacturer. Figure 4.2 below shows a JSS model according to our general manufacturing model. The dash lines identify the important system interfaces.

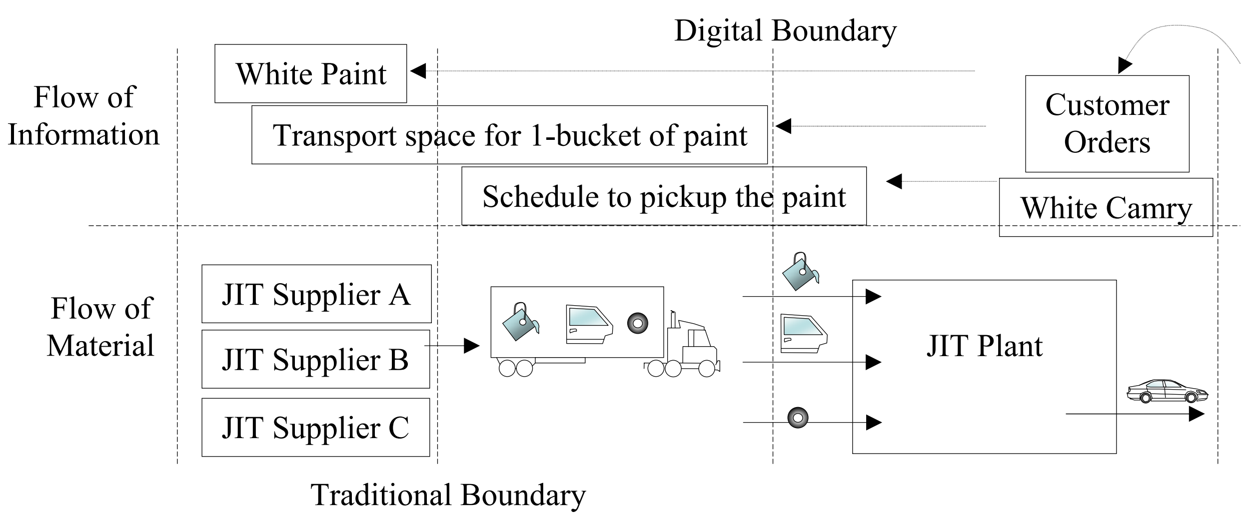


Figure 4.2: A JSS Model

Using the JSS Model above as a principle guideline, a discrete simulation model is built to the model to study the detailed operations and dynamics of the system.

4.3 Components of JSS Model

This section describes a discrete event simulation model based on the JSS model outlined in the previous section. The simulation tool employed to construct this model is the ARENA / SIMAN software package. ARENA is the interface to the SIMAN language. The software has been used in academic research as well as industrial simulation projects. Even though a particular simulation tool is used, the generality of the concept and design remains intact. The advantage of using a simulation tool is that it allows us to build our simulation model concisely with reduced coding effort. The disadvantage is that the tool may restrict the model with unwanted built-in functions, though the problem can generally be resolved through clever workarounds.

Figure 4.3 below represents a one-supplier, one-part-source JSS model, which consists of six sub-models: production, supplier, route, plant, kanban, and consumption. Each sub-model is divided based on the boundaries and interfaces described in Figure 4.2, including the route sub model and kanban sub-model. The supplier, production, consumption, and plant sub-models describe the flow of material. As their names suggest, the production sub-model produces parts. The supplier sub-model monitors and manages trailers arrivals and departures at the supplier. The plant sub-model handles trailer arrivals and departures at the plant. The consumption sub-model simply consumes the parts. The route and kanban sub models describes the flow of information. The route sub model schedules the trailers; the kanban sub-model reorders parts.

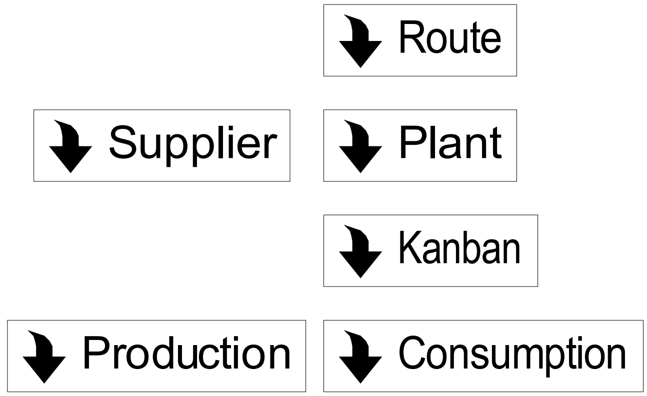


Figure 4.3: JSS Discrete Event Simulation Model

The entities of the model are parts, kanban, trailers, and cycles. Parts are produced in the production sub-model and they are consumed in the consumption sub-model. Parts are shipped from the production sub-model to the consumption sub-model. In transit, they go through the supplier sub model, and the plant sub model. Kanban controls the reordering of parts. All kanban cards start and end in the kanban sub-model. Trailers transport the parts and the kanban cards from the supplier sub-model to the plant sub-model. Cycle entities signal the transport cycles and they only exist in the route sub-model; they specify the time to dispatch a trailer.

4.3.1 Production Sub Model

The production sub-model models the production operations at the suppliers. Figure 4.7 shows the production sub-model. The model employs a number of prototype parts that waits in a queue for a signal from the kanban system. Once a signal is given, the parts duplicate themselves to the quantity required. The duplicates are delayed in a process block to simulate the production lead time. After that, they are batched and held in another queue for pickup.

4.3.2 Supplier Sub Model

The supplier sub-model models trailer docking operations. Figure 4.4 shows the supplier sub-model. The model waits for trailers entities to arrive at the station. A Trailer drops off its kanban cards and proceeds to a docking process. The model sorts through the kanban cards for a particular supplier and sends the cards to a kanban hold queue. The rest of the kanban cards go directly to an exit holding queue. The kanban hold queue waits for a docking complete signal from the trailer to begin processing the kanban cards. The due kanban cards are assigned a batch of parts from the production sub-model and sent to the exit holding queue. Sometimes, there is no part at the production sub-model, because the demand exceeds the level of production. If there is no part at the production sub-model, the kanban card proceeds directly to the exit holding queue. A kanban card with no part will be sent back to the plant, while a new kanban card is issued at the plant for the next trailer to recover these parts. Once the kanban cards are processed, the next event allows the trailer to pickup the kanban cards and their parts. Then, the trailer leaves the sub-model. Since the kanban sub-model regulates the number of kanban cards per trailer, it automatically limits the number of kanban cards in each trailer.

4.3.3 Route Sub Model

The purpose of the route sub-model is to control the timing of the trailer departure. The route sub-model creates an entity, named cycle that signals the time for one of the trailers to begin the transport cycle. The signal occurs periodically with its duration set by a delay block. Figure 4.5 shows the route sub-model.

4.3.4 Plant Sub Model

The plant sub-model manages the trailer launch and unloading operation. Figure 4.9 shows the plant sub-model.

Trailers are created at the plant. Once created, the trailers are held in a queue waiting for the cycle entity in the route sub-model to signal the trailers for transport. After a trailer receives its signal, it is first assigned a route based on the signal. Then, the trailer signals all the relevant kanban queues for parts transported on that route, requesting release of the corresponding kanban cards. After that, the trailer picks up the cards and starts requesting for a carrier. The carrier takes the trailers to its first and subsequent destinations on the route. Note that the carrier is a resource that moves a trailer from one station to another. Carrier can be used to simulate transportation delays and break downs.

In this model, trailers arriving at the plant are unloaded at a dock immediately. The trailers first free their respective carriers, before dropping off all the kanban cards and parts. After that, the trailers go back to the holding queue.

4.3.5 Kanban Sub Model

The kanban sub-model describes the kanban system. Its function is to receive and send kanban cards as signals to authorize production and transfer parts from suppliers to the manufacturer. Figure 4.6 shows the kanban sub-model. Kanban cards are sent through signals from the consumption sub-model and the plant sub-model. The consumption sub-model put the kanban cards in a reordering queue; the plant sub-model signals the release of the reordering queue to be picked up by the trailers. The kanban cards travel with a trailer to a particular supplier. The supplier processes the cards and returns them with parts with the trailer. When the trailer unloads in the Plant sub-model, the cards are released back to the kanban sub-model where they wait for consumption to occur before being released again.

4.3.6 Consumption Sub Model

The consumption model simulates the consumption of parts inside the plant. Figure 4.8 shows the consumption sub-model. The sub-model consists of a consumption point process with two queues that represents the inventory level at the consumption point and the inventory level at the dock or staging area. The queue at the staging area regularly scans the inventory level (the other queue) at the consumption point. If the inventory level at the consumption point reaches a critical point, parts are released to the consumption point and a reordering signal is triggered to the kanban sub-model.

The parts are consumed according to a predetermined demand distribution. The demand is generated by a create entity block that also simulates the production flow to the consumption point. A disposer destroys the parts after a delay process. The delay process simulates an application of a part at the consumption point.

4.3.7 System Flows

As mentioned earlier, kanban controls the reordering of parts. The flow of the kanban cards is as follows: A kanban card is issued in the kanban sub-model when inventory level hits a critical point. At a specific time, a trailer will pickup and transport the card to its designated supplier. The supplier is where the trailer drops off the card. The card stays at supplier for a number of cycles to simulate the order-to-pickup lead time. After that, another trailer picks up the card together with any available parts assigned to the card. The trailer then returns to the plant and drops off the card. The card is returned to a collection bin, i.e. a HOLD block that accumulates all the extra cards.

The parts are produced at the supplier. The flow of parts is as follows: A prototype part duplicates another part once a kanban signal is issued. This occurs at the same time that the kanban card is issued for the kanban flow. The part is delayed in a process block to simulate production. It then goes to a batch block and becomes part of a pallet. The pallet is picked up by a trailer at a specific time and travel together with its kanban card to the plant. At the plant the pallet is dropped off and moved to a holding block in the consumption sub-model.

Figure 4.4: Supplier Sub Model

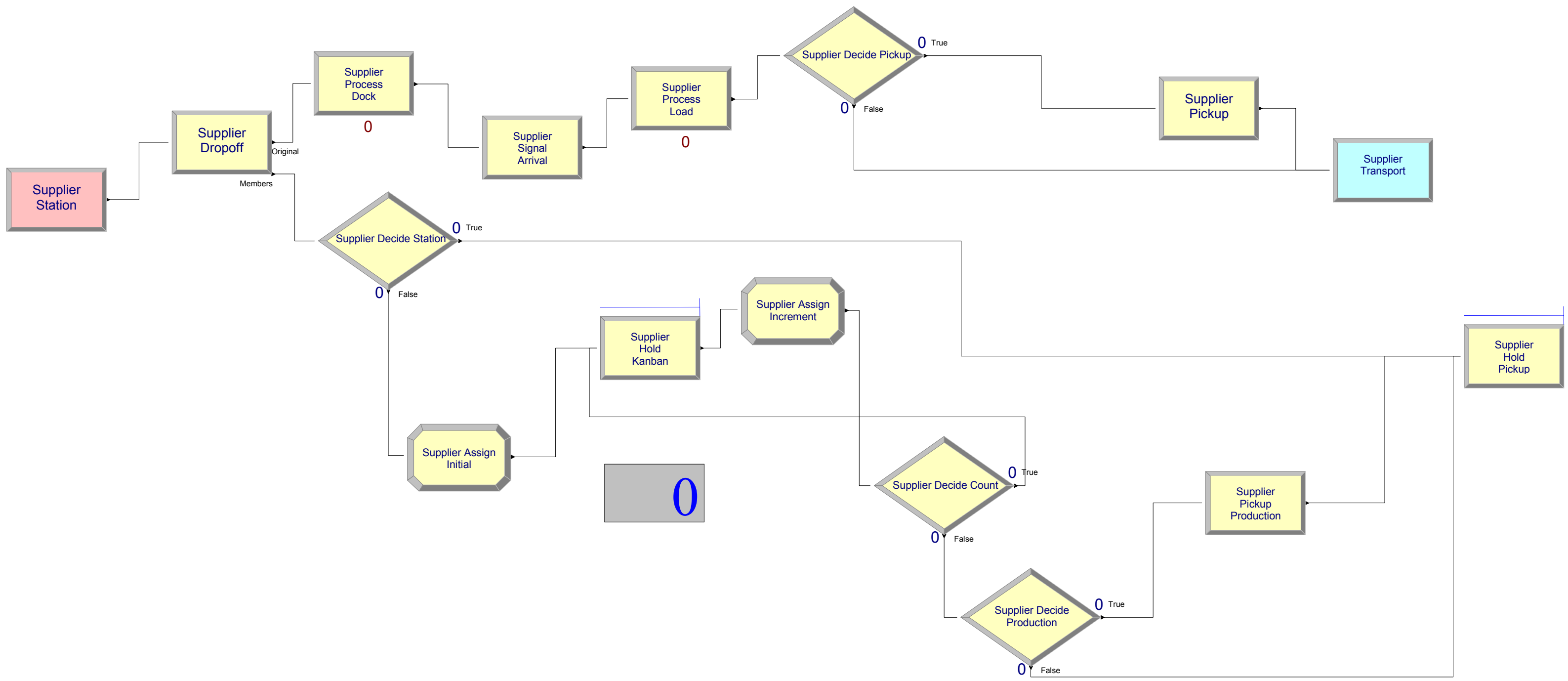


Figure 4.5: Route Sub Model

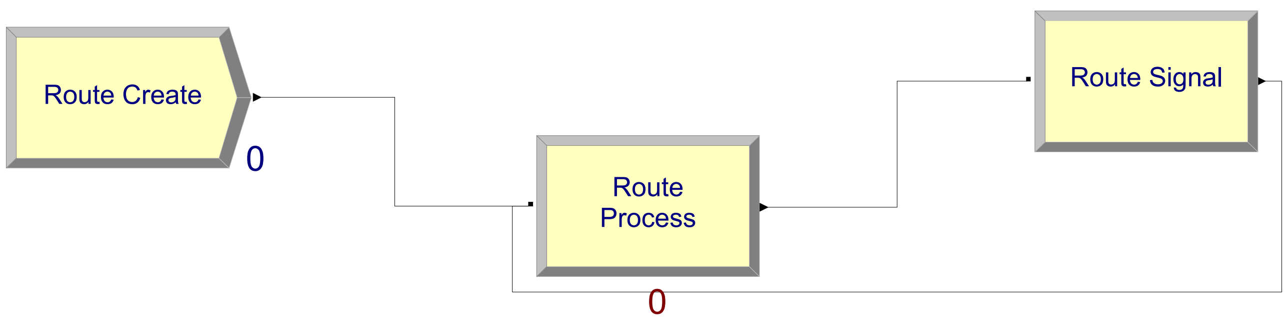


Figure 4.6: Kanban Sub Model

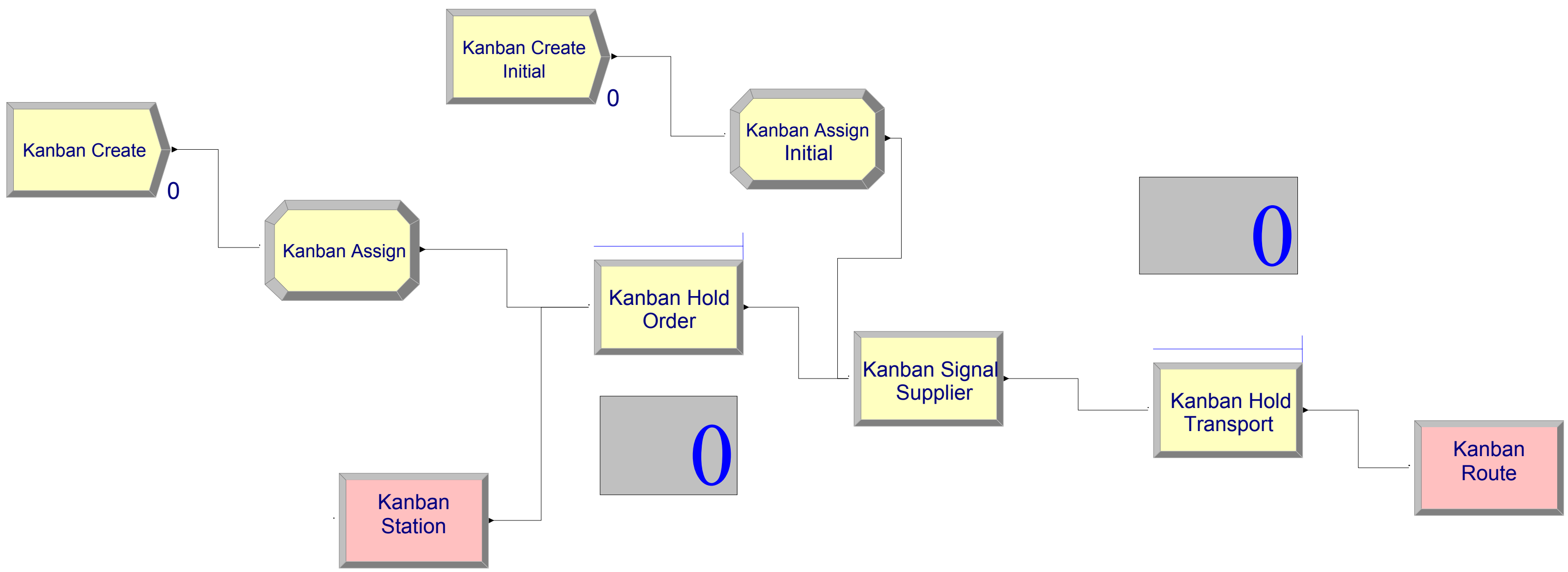


Figure 4.7: Production Sub Model

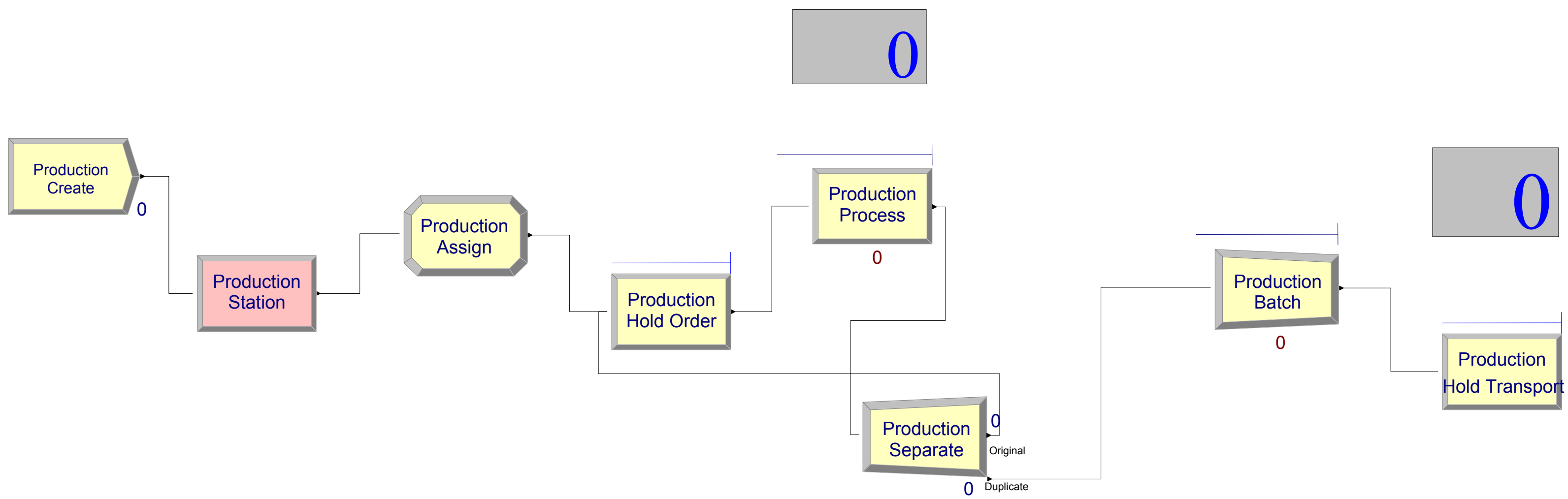


Figure 4.8: Consumption Sub Model

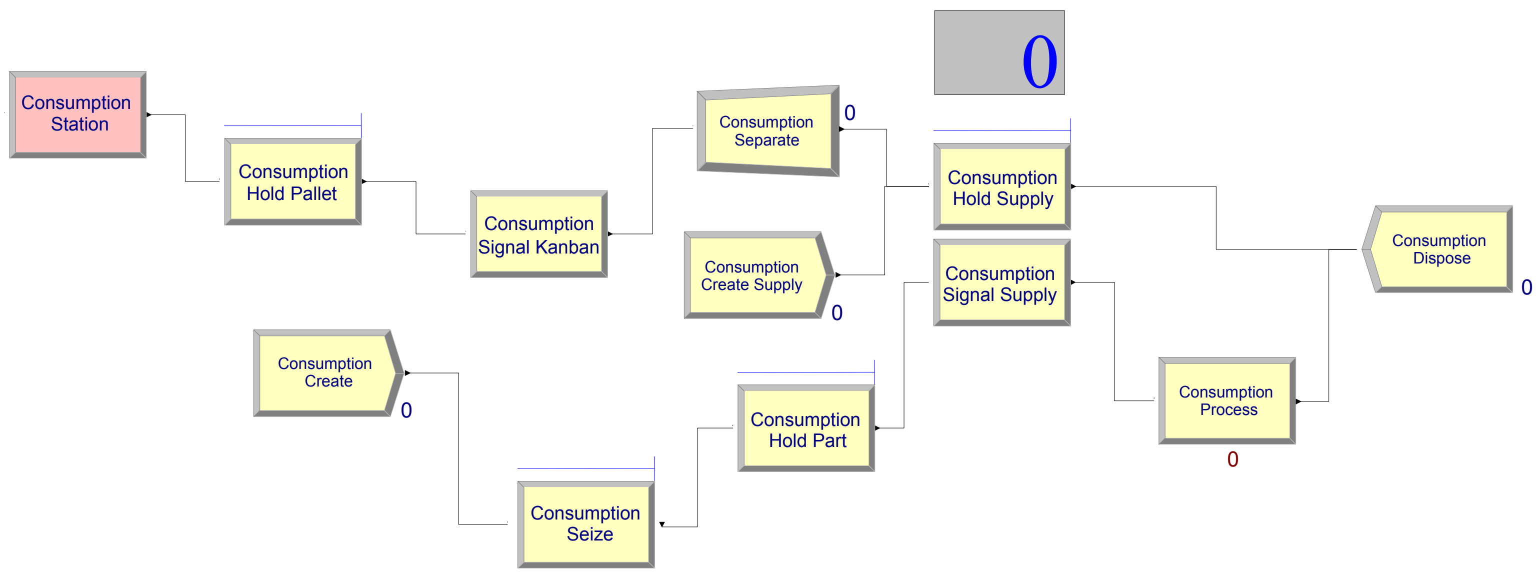
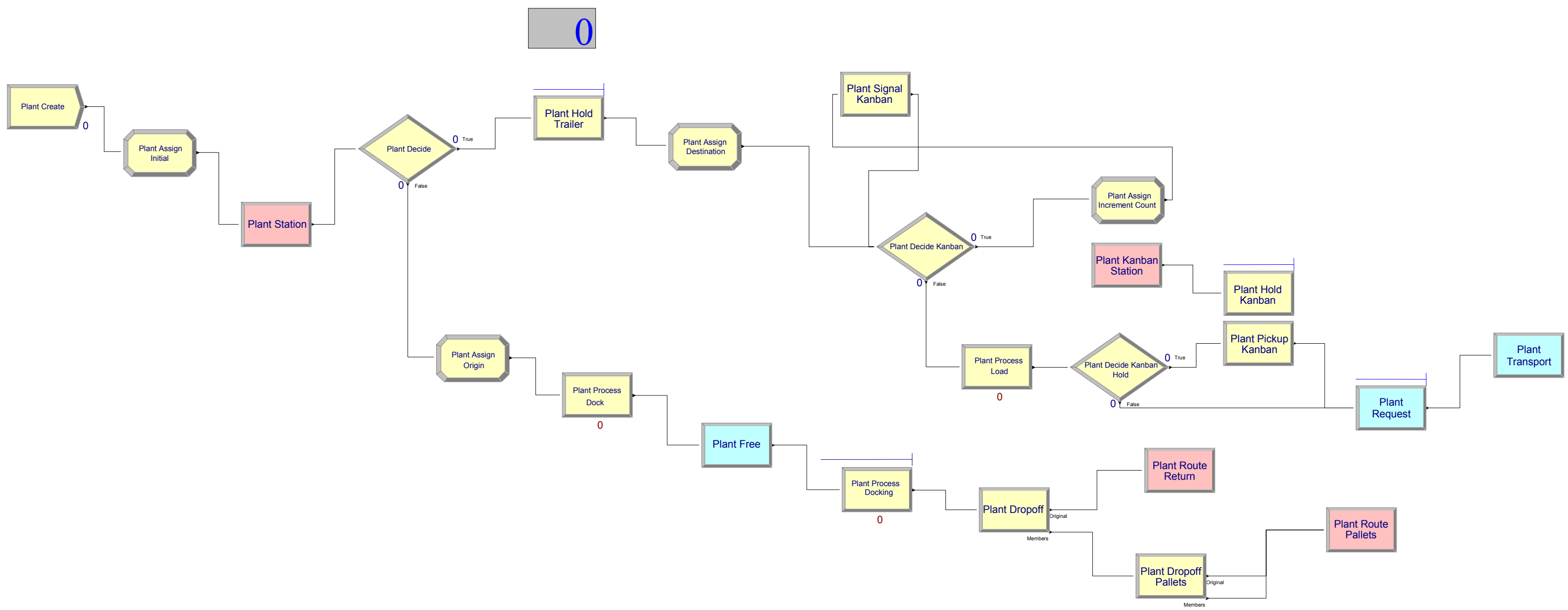


Figure 4.9: Plant Sub Model



4.4 Simulation Experiments and Results

We simulate a single supplier, single part model. The simulation contains five replications. The first simulation is for reference. The random variables in this model are the demand which is a exponential distribution with a mean of 50 seconds or EXPO(50). Nevertheless, the process at the production line is a normal distribution with the same mean but a standard deviation of 0.2 or NORM(50, 0.2). The effect of the production rate reduces the demand variation of the parts from the suppliers. After this simulation, we will analyze the impact of supplier and transportation by modifying the model.

We assume that there is a production line that requires on averaged a part every 50 seconds with a supplier of similar process capability. Hence, the production and consumption rate is 1 part every 50 seconds. The traveling time between the supplier and the plant is 1400 seconds. The unload delay at the plant is 400 seconds. The loading and unload delay at the supplier is 100 seconds. The loading delay at the plant is 50 seconds. Therefore, the lead time between the supplier and the plant is 3350 seconds (about 56 minutes). It happens that a container for the part can hold 4 parts. Thus, the kanban size is 4 parts per kanban card. From the route design, the trailers run every 400 seconds and each trailer can pick up 2 containers on each run. Note that these numbers can be scaled without affecting the characteristic behaviors of the system.

With the above parameters, we determine that the following numbers are able to handle the transportation. The reordering level is set at 120 parts for the time being to ensure that there is an ample of room for backlog. Since the trailers arrive at the supplier every 400 seconds with a request of 8 parts, the minimum ordering lead time at the supplier is after 1 trailer pickup or 400 seconds. For the benefits of the supplier, we set the ordering lead time to after 4 trailer pickup. This adds 1600 seconds to the lead time for a total of 4950 seconds.

At the beginning of the simulation, there are 120 parts at the plant and all the trailers are waiting at the plant to be dispatched. The kanban post is initialized with 28 cards, such that about 2 cards (containers) worth of inventory is maintained at the staging area. Figure 4.10 shows a plot of the inventory level at the consumption point in the plant against the simulation time in seconds. The complete simulation result is in Appendix D.

From the figure, we can see that the initial inventory level is at 120 parts with no trailer on the road. The initial drop of inventory is due to the backlogged trailers in the warm up period. As mentioned earlier, the trailer leaves the plant every 400 seconds, but in the beginning all the trailers are in the plant sub-model. From the graph, a warm period of 20000 seconds is required to account for the backlogged trailers.

The graph in the figure also shows that the inventory level sticks to a certain level, but then makes sudden increase without warning. It seems that what we are observing is that if the system permits a high inventory cap, then because of contingencies it is possible that that large cap will permit inventories to creep up and perhaps even reach the cap. Moreover once they rise, they "stick there" and do not come back out. In some runs, the inventory level eventually increases to the set level due to disruptions of the production rate. If the reordering level is not lowered, the inventory level may stay at a high level like waste.

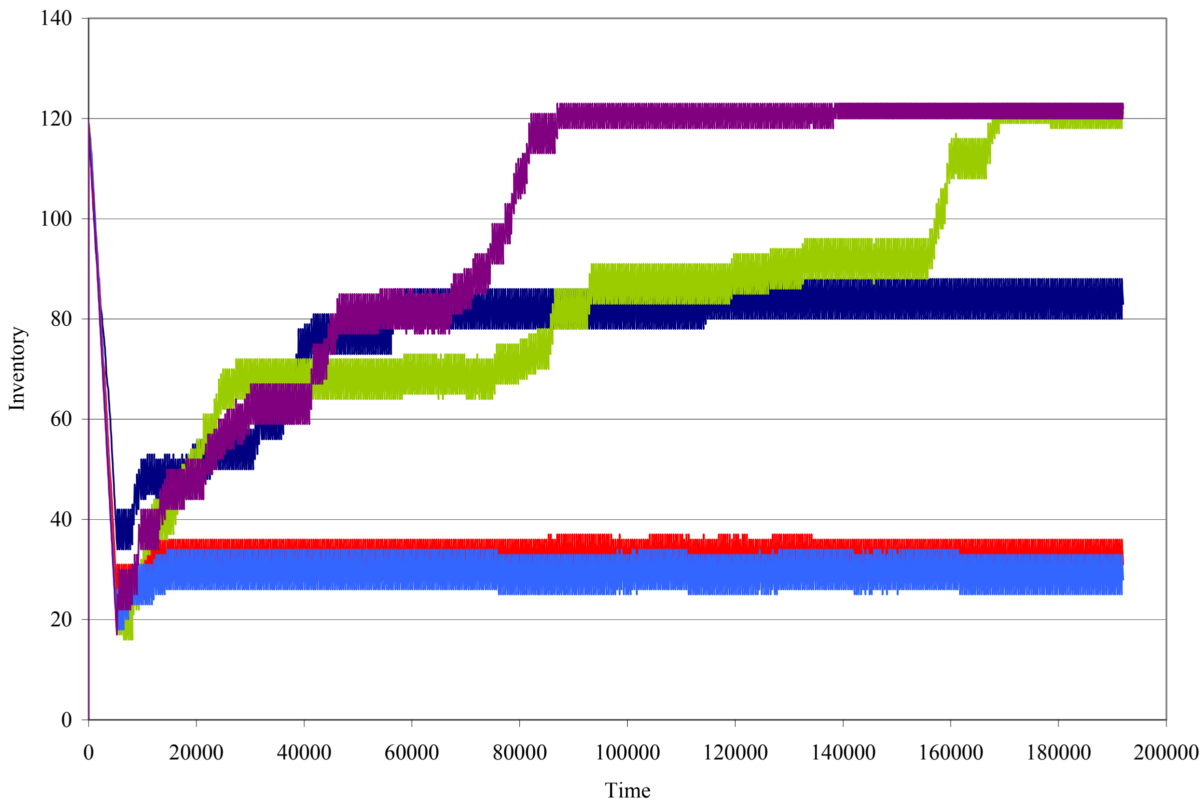


Figure 4.10: A Plot of Inventory Level at the Plant against Time

The mechanism of the reordering level is causing the inventories to reach the cap. The way in which the inventory increases shows that the kanban system is a mechanism that can control the rate of supply, but not in the amount supplied.

We performed some calculations to check out the model for correctness. For the input parameters, we can determine the average number of kanbans needed by the system using Toyota's supplier kanban equations. For reference, Toyota defines delivery cycle as A-B-C, where A = required delivery frequency, B = number of delivery in A, and C = the conveyance interval. The average number of kanban cards needed is given by the following equation:

$$N = (AD) * (A / B * (1 + C)) / KS$$

, where AD = average production rate and KS = number of parts per kanban card. (A / B) * (1 + C) is the cycle time. Observe that the Toyota's equation is Little's Law (WIP = TR * TT) in disguise (if we let WIP = N*KS, TR = AD, TT = (A / B) * (1 + C)).

The conveyance interval, C is the lead time (4950 second) divided by the delivery interval (400 seconds). The "1" in (1 + C) corresponds to the wait at the kanban post. The required delivery frequency, A, and the number of delivery, B, is easier to understand if we let (A / B) be the delivery interval. The reason that Toyota uses two parameters to represent the delivery interval is that they want to separate it into the long term cycle (A ~ daily, weekly, etc.) and the short term cycle (B ~ first run, second run, etc). Therefore, in this model, N = 26.75, with AD = 1 / 50, KS = 4, A / B = 400, C = 4950 / 400.

Table 4.1 below verifies the kanban counts in the kanban sub model. There are a total of 31 kanban entities in the system. Assuming that a full truckload of parts (equivalent to two cards of kanban) is at the kanban staging area, the average number of kanban cards used by the model is the total number of kanban cards – number of unused cards + number of kanban cards at the staging area, or N = 31 - (3 + 3.2501) + 2 = 26.7499.

Table 4.1: Results of the kanban counts in the kanban sub model

Identifier	Average	Minimum	Maximum	Final Value
Replication 1 of 5				
Kanban Hold Transport	3.2501	2.0000	4.0000	2.0000
Kanban Hold Order	3.0000	3.0000	4.0000	3.0000
Replication 2 of 5				
Kanban Hold Transport	3.2499	2.0000	4.0000	2.0000
Kanban Hold Order	3.0000	3.0000	4.0000	3.0000
Replication 3 of 5				
Kanban Hold Transport	3.1991	2.0000	4.0000	2.0000
Kanban Hold Order	3.0507	3.0000	4.0000	3.0000
Replication 4 of 5				
Kanban Hold Transport	3.2499	2.0000	4.0000	2.0000
Kanban Hold Order	3.0000	3.0000	4.0000	3.0000
Replication 5 of 5				
Kanban Hold Transport	2.3904	.00000	4.0000	.00000
Kanban Hold Order	3.8596	3.0000	6.0000	5.0000

It is clear that the consumption point does not need to keep 120 parts as inventory. In the next model, we reduce the reordering level to one container or 4 parts. As expected and as shown in Figure 4.11 below, the inventory level stabilized.

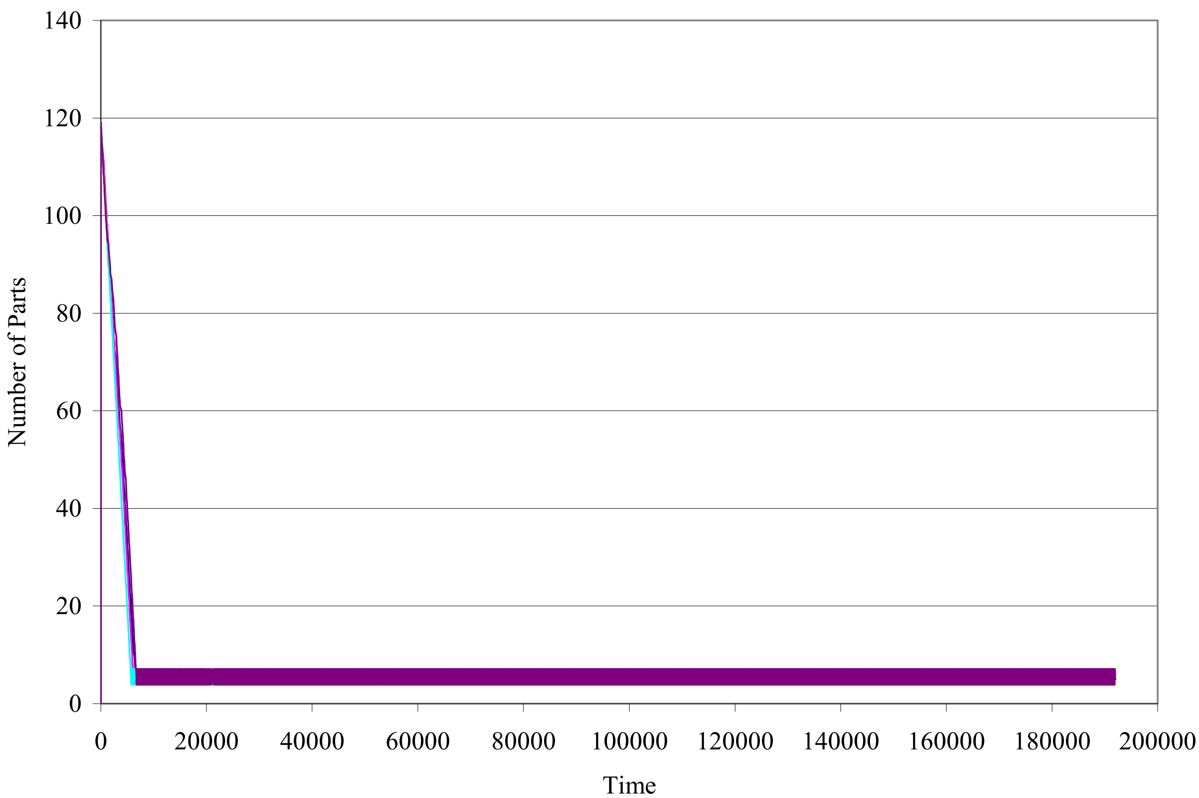


Figure 4.11: A plot of inventory level verse time with 4 parts buffer.

Nevertheless, some parts start to accumulate in the staging area. Previously, all the parts at the staging area went to the consumption area due to the high reordering point. Figure 4.12 below shows the inventory level at the staging area. Note that the parts at the staging area are still bundled in pallets. Thus, the y-axis is the number of pallets. At the standard condition, there should be two pallets at the staging area. The graph shows some spikes due to the changes in demand at the consumption point. At no point in time does the number of pallets at the staging area fall below one. This indicates that the consumption point is never starved of parts.

Hauser shows that the dispatching operations at the staging area are more complex than that in our case because there are cross-docking pallets that consist of parts to several consumption points (Hauser, 2002). Bundling of different parts into a pallet is decided by the packaging department and often happens to low volume parts. Since our simulation only has one consumption point, the dispatching of parts is not an issue.

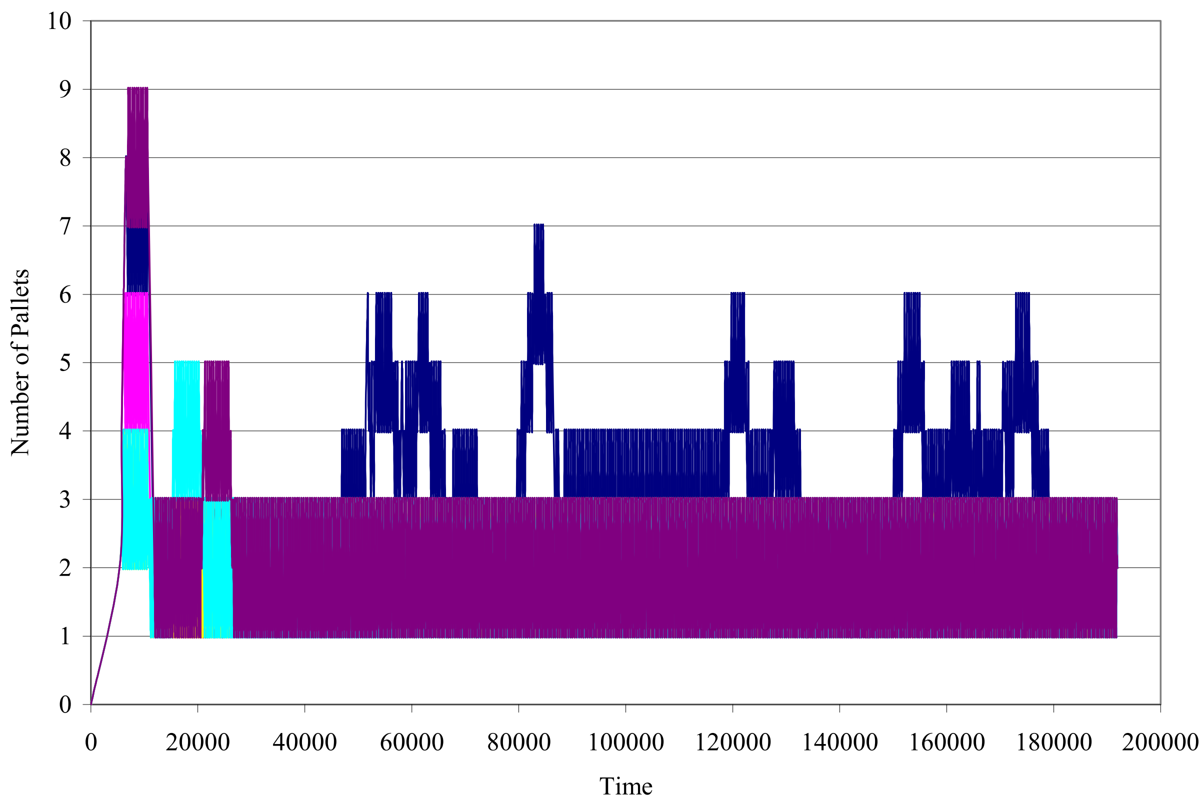


Figure 4.12: Inventory level at the staging area verse time with 4 parts buffer

4.4.1 Unreliable Supplier

In the next simulation, we will study the effect of supplier performance on the system. Suppose that there is an unreliable supplier that cannot consistently maintain the production rate of one part every 50 seconds, but is able to do it on an averaged basis. The production rate can be modeled as a gamma distribution, i.e. $50 - \beta + \text{GAMMA}(\beta, 1)$, where β varies from 10 to 50.

Figure 4.13 below shows the effect of unreliable supplier on the inventory level.

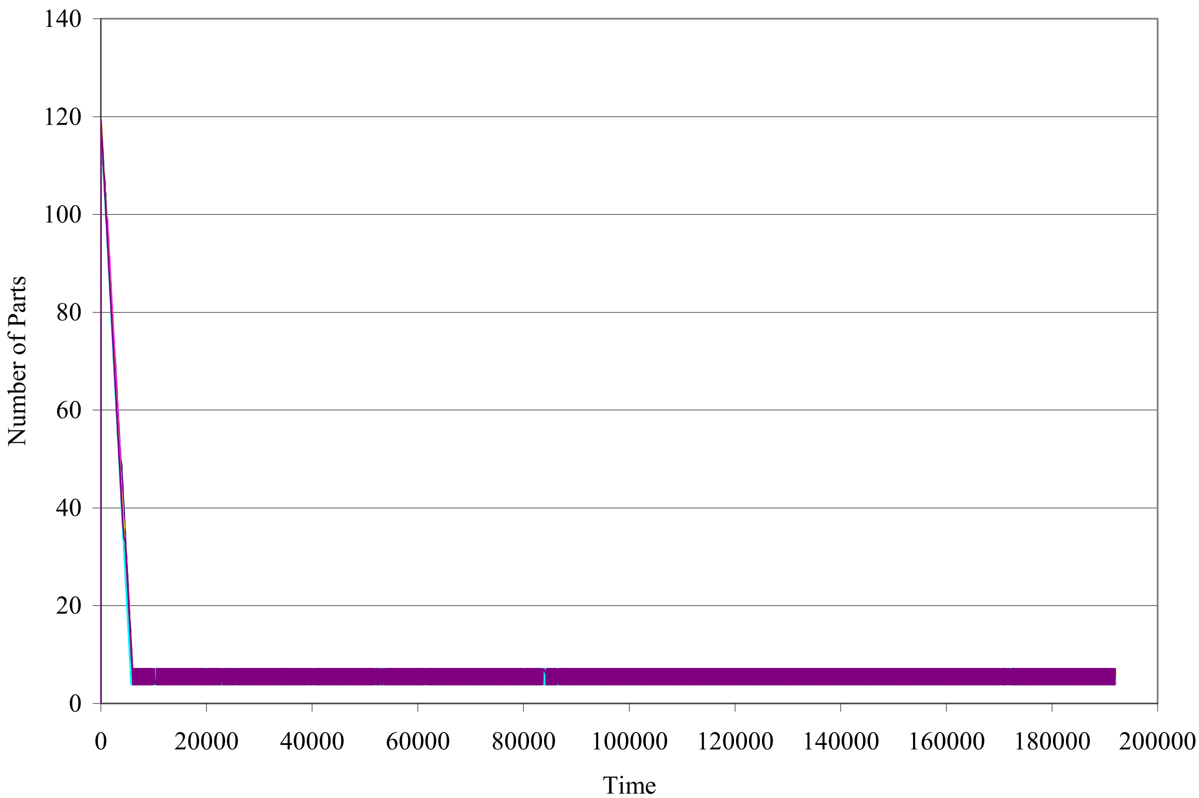


Figure 4.13: Inventory level verse time with 4 parts buffer and unreliable supplier

Figure 4.13 is very similar to Figure 4.11, which indicates that the supplier does not play a major role in the stability of the plant system. To explain this phenomenon, the lead time of the system is 4950 seconds. The production time on averaged is 200 seconds. Even if we reduce the lead time to 3350 seconds for immediate pickup upon the received of the kanban card, the supplier is still able to make the shipments for a very disperse gamma distributions. Therefore, the effect of supplier performance is negligible, unless the supplier is unable to maintain the production rate. Figure 4.14 shows the inventory level at the staging area.

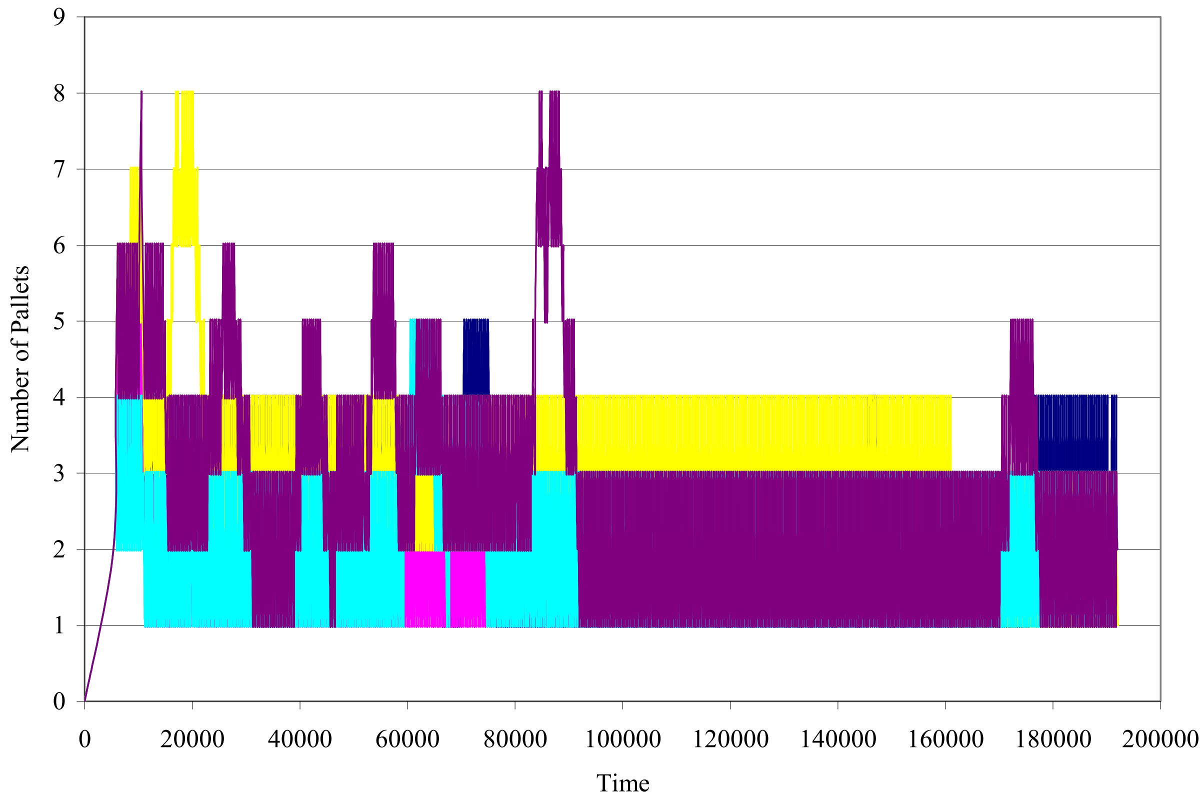


Figure 4.14: Inventory level at the staging area with unreliable supplier

In this case, we can see more spikes than before, showing some of the effects of unreliable supplier. Nevertheless, there is no stock out.

4.4.2 Unreliable Transportation

In the next simulation, we will study the effect of transportation performance on the system. Suppose that the transportation is unreliable and the trailer cannot consistently arrive on time. The transportation delay is modeled as a change in speed of the trailer on the road. The distribution of the speed of the trailer is 1.1 – GAMMA(0.1, 1).

Figure 4.15 below shows the effect of unreliable supplier on the inventory level.

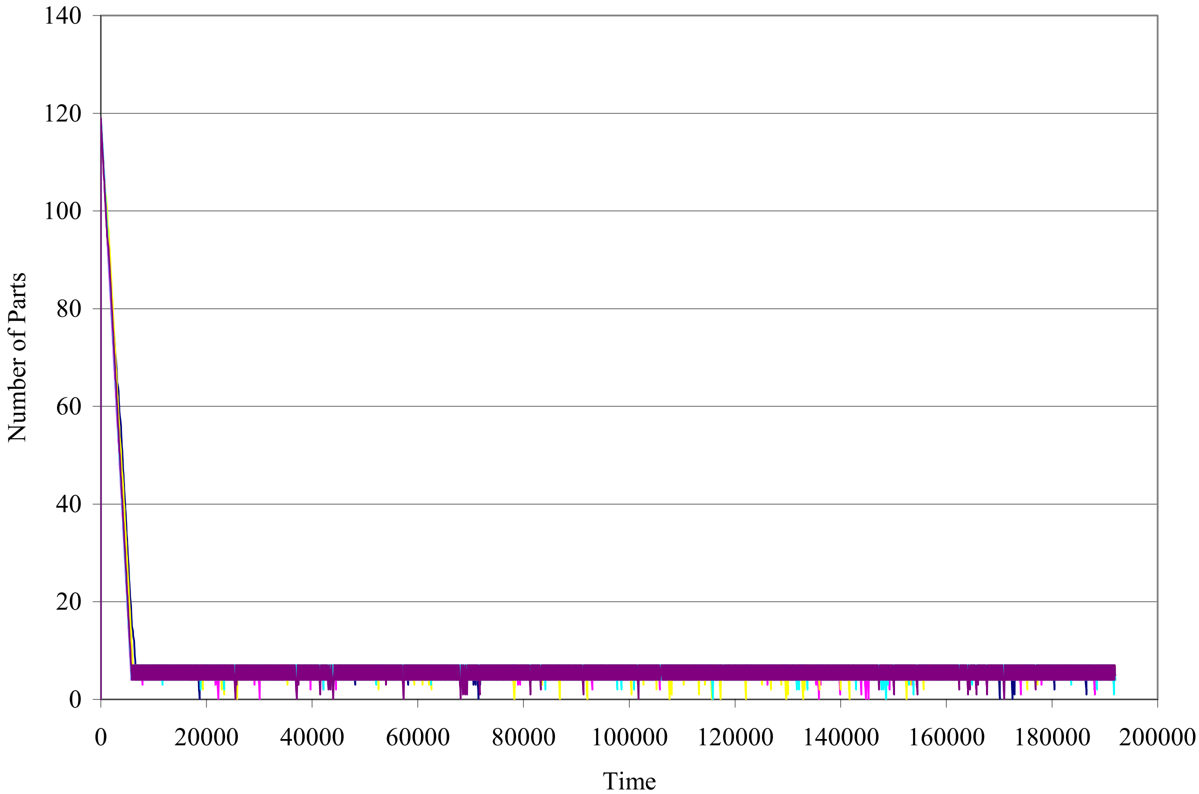


Figure 4.15: Inventory level verse time with 4 parts buffer and unreliable transportation

In this case, there are many stock outs. The staging area is unable to shield the variation from production line anymore. Figure 4.16 shows the inventory level at the staging area.

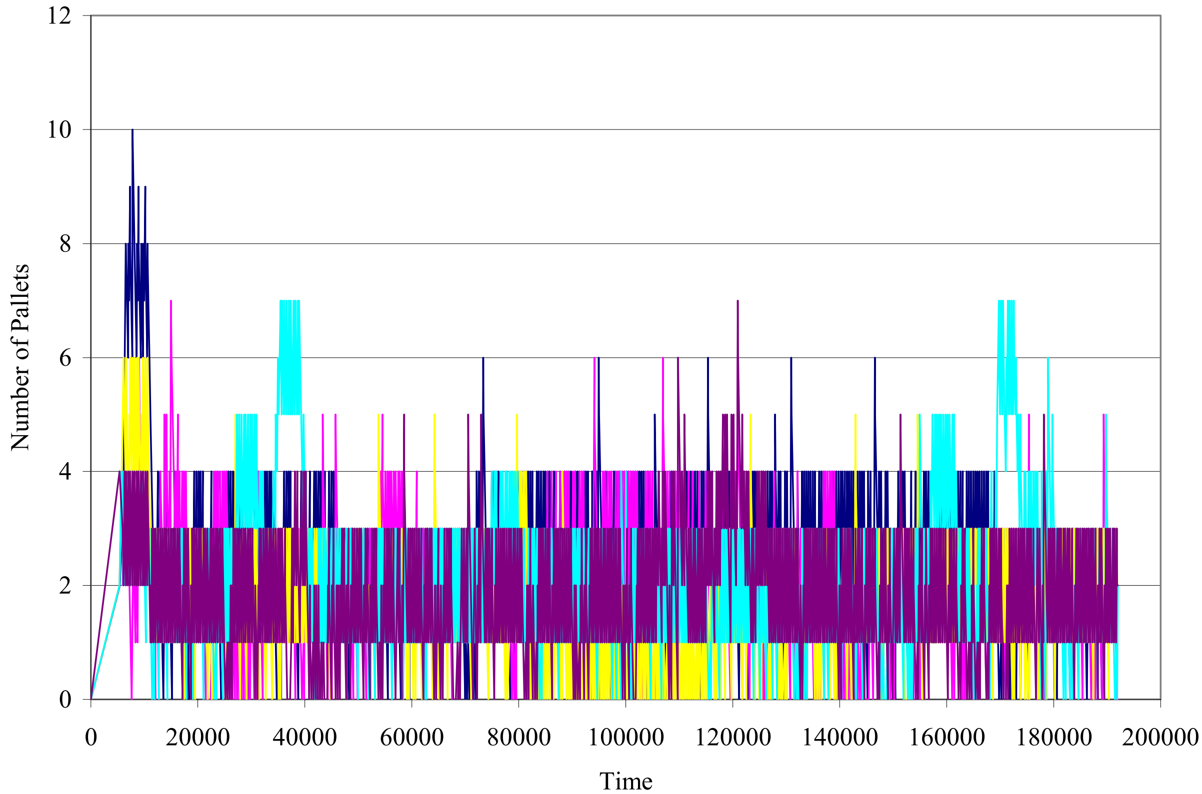


Figure 4.16: Inventory level at the staging area with unreliable transportation

It makes sense that since the transportation is closer to the plant, it has greater effect on production. One solution to restore reliable transportations is to relax the schedule such that the trailers always arrive early. This is applied at Toyota, but such a solution creates sleep time in the system, increasing the inventory.

4.5 Simulation of a Surge in Demand during Changeover

In this simulation, we will study the effect of a sudden surge in demand on the system. We are interested in how fast the system is able to cope with such a change. In practice, this is an issue for JSS during the routes changeover period that occurs upon expiration of a planning interval (once every four weeks at Toyota). To model the effect, we assume that the consumption rate at the plant is going to increase from 50 seconds per part to 40 seconds per part. The change will increase the averaged number of kanban cards, according to the Toyota ABC equation, from 26.75 to 33.4375.

The point selected for the surge in demand is at time 100000 seconds. To show the effect clearly, the inventory level has been raised to 24 parts. Seven cards are inserted into the system at the onset of the surge. The number of cards a trailer can carry is increased by one to three. Figure 4.17 shows the effect of the surge.

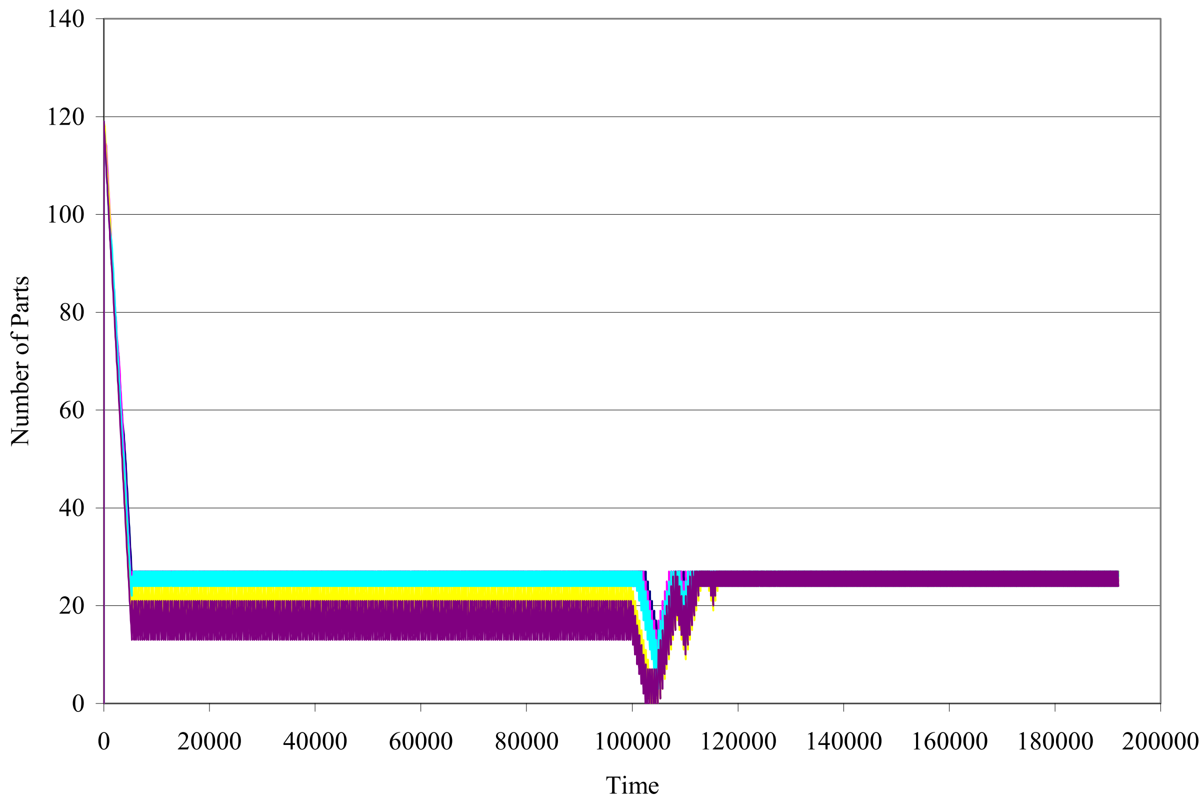


Figure 4.17: Inventory level verse time with 24 parts buffer and changeover

As point out earlier, the changeover is a disruptive period of the system. Although we do not simulate route change, demand change is enough to upset the system. In addition, the disruption is long term (4 complete route cycles) and has after effects that come in waves, each wave smaller than the prior one. For a typical Toyota case of four weeks, as soon as the effect dies out, the routes expire. Figure 4.18 enlarges the fluctuations in Figure 4.17.

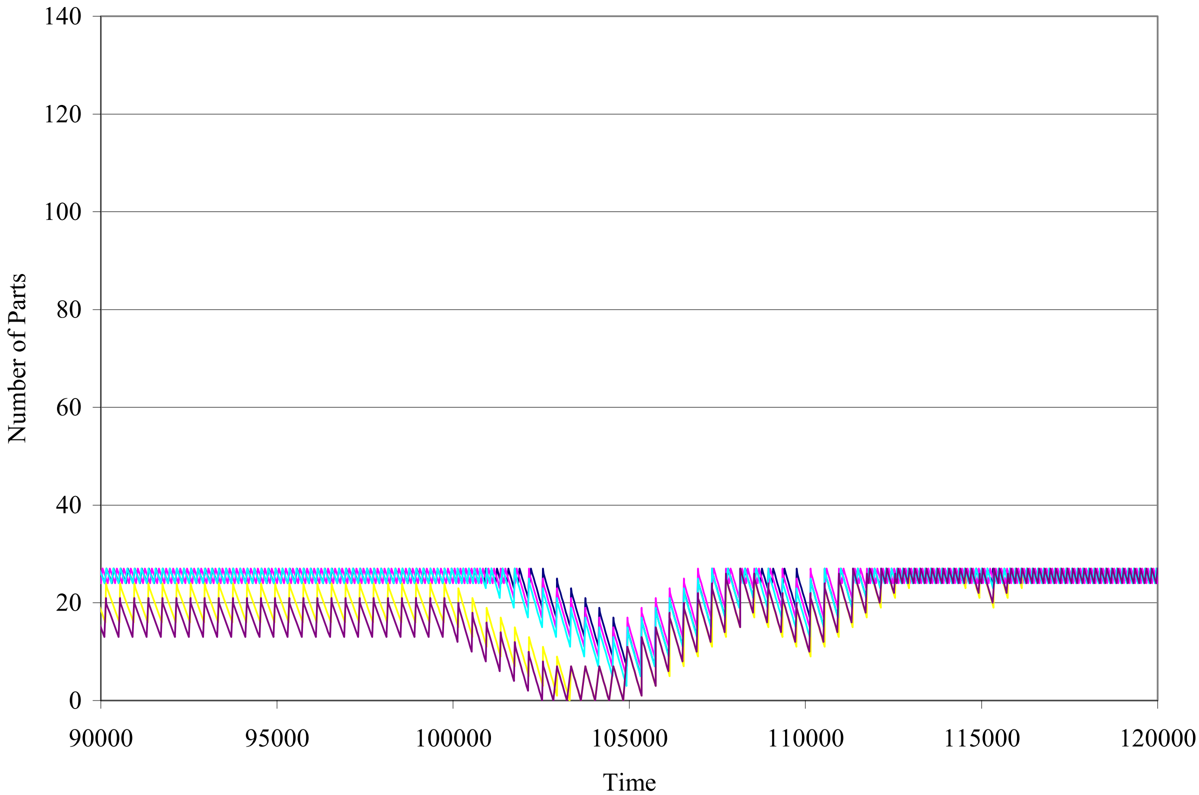


Figure 4.18: Enlarge figure of the inventory level at the time during the changeover

After examining the simulation model in detail, we found that the effects are due to parts accumulation. When the demand increases, more kanban cards are issued to each trailer until it is 100% full. Since each trailer can hold a small amount of safety stocks, parts accumulate for the next few trailers in the route until the system used up all the allocated kanban cards. The imbalance causes some trailers to carry more parts than the other as shown in Figure 4.19.

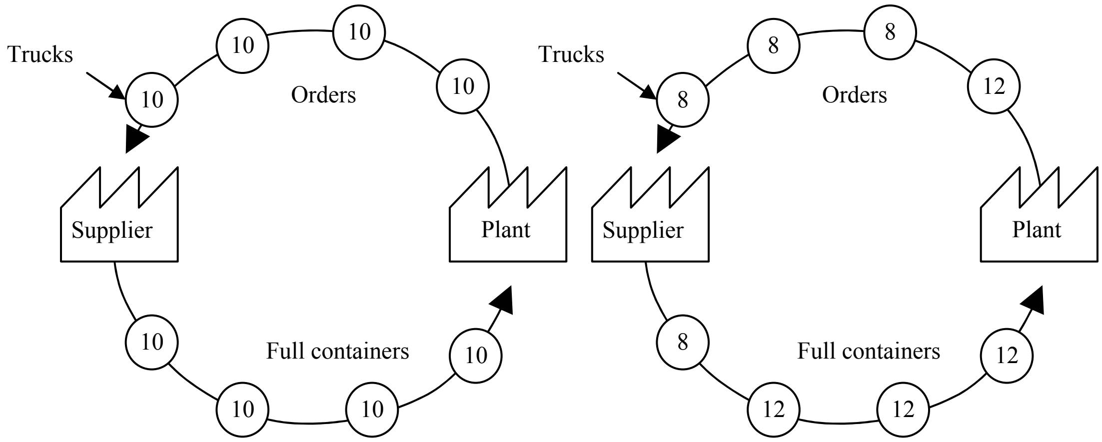


Figure 4.19: Parts can accumulate in a route group

At the staging area, the inventory also fluctuates up and down from a maximum of 4 pallets to no pallet during this time. Figure 4.20 shows the inventory level at the staging area.

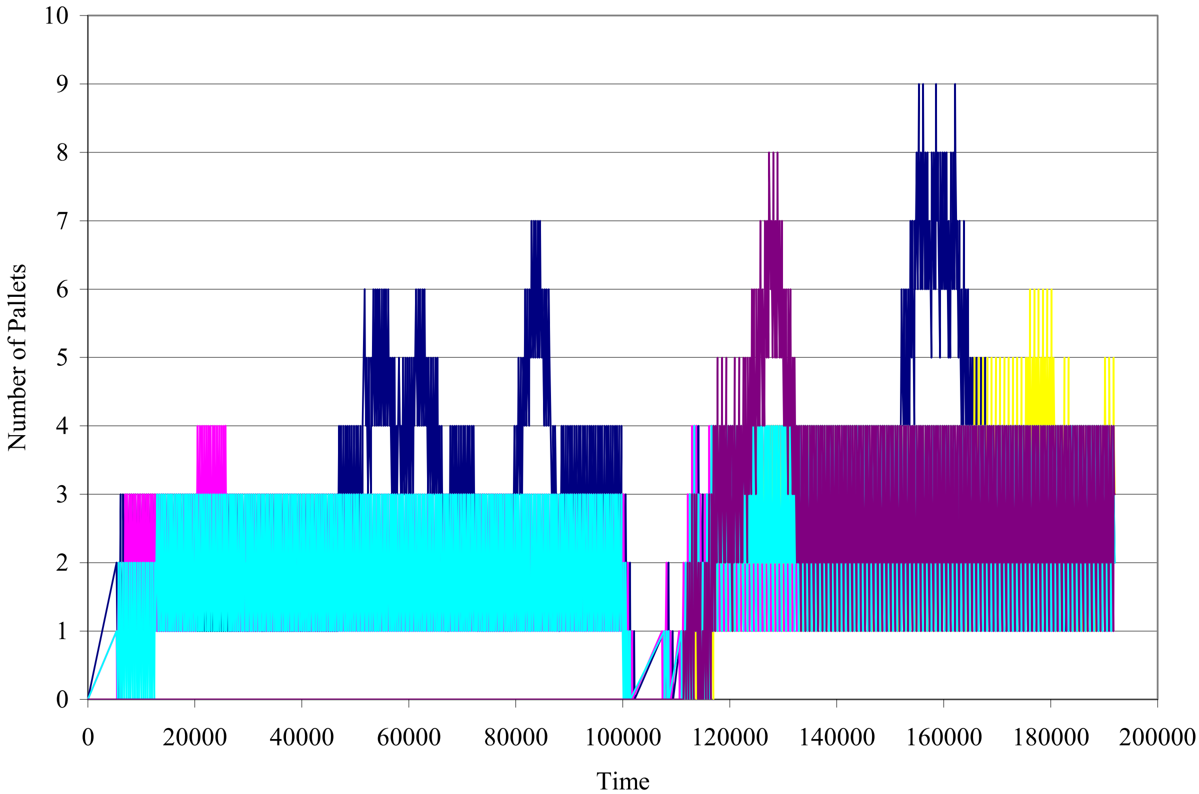


Figure 4.20: The inventory level at the staging area with changeover

To correct the system, instead of introducing the seven cards at the onset of the surge, one card is added every 600 seconds up to the point of surging. The route change has also been brought forward to accommodate the new cards. Note that without route change, the new cards will not be picked up by the trailers as efficiency due to the trailer capacity limit. With these changes, we are able to reduce the fluctuations significantly, including the after effects. Figure 4.21 shows the improved results.

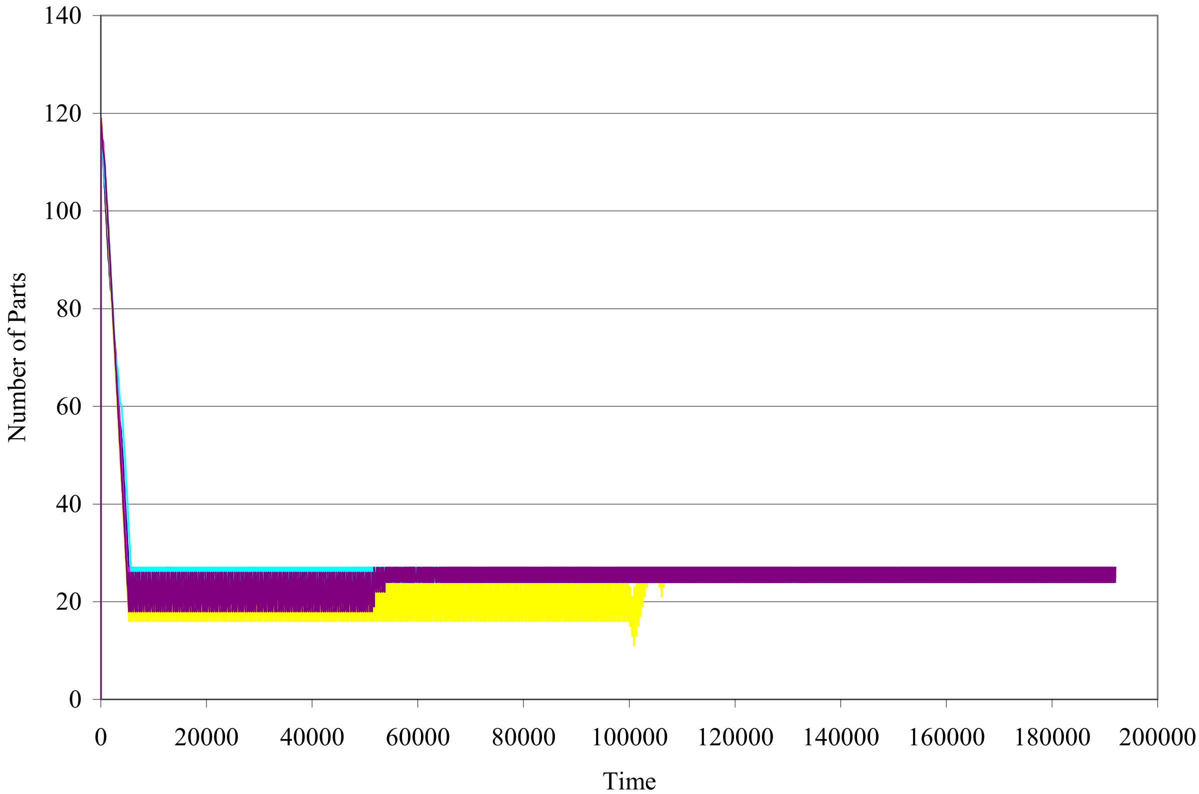


Figure 4.21: Gradual introduction of change smooth the inventory level

4.6 Summary

The above results show that the system's inventory level tends to stick to an arbitrary level. At worst, the inventory level is at the reordering level. Overall, JSS is very stable, but to perform well it requires reliable transportations. One solution to enable a reliable transportation is to relax the schedule such that the trailers always arrive early. The solution however creates sleep time in the system. We also demonstrate the effect of changeover in the system due to demand increase. The impact to inventory level from changeover is relatively long term and only dissipates after several waves of fluctuations in the inventory level.

Chapter Five: Conclusions and Discussions

5.1 Contributions

In this dissertation, three heuristics algorithms are developed and solved. They are an ant colony optimization algorithm for common frequency routing (CFR), a taboo search algorithm for general frequency routing (GFR), and a taboo search algorithm for Cross-dock routing (CDR) with CFR. Note that mathematical formulations for GFR and CDR have also been developed as part of this dissertation. The formulation for CFR was developed previously by the author in his master thesis. The results, as shown in chapter 2, reveal that GFR routes at high frequency, low-space condition's do not have common frequencies in the solution. Each route is very different from one another. At medium frequency with a medium amount of space, some routes have a common frequency. As the space increases from medium to large, the solution moves toward vehicle routing solutions. By comparing CFR and GFR solutions for the same problems particularly for high frequency with large space allocations, one would question whether small cost savings are worth the additional complexity of GFR results. It is proven that CDR is an extension of VRP type problems that can be solved quickly, especially with meta-heuristic approaches. Nevertheless, from a cost perspective CDR is only useful for extending the suppliers' time windows. In general, CDR, and CFR are practical routing strategies for JSS. They can be solved in reasonable time with taboo search or other types of meta-heuristics. GFR solution approaches encounter difficulty when space limits are small and high frequency solutions are required.

We have shown that the impacts of CFR restrictions are minimal. In chapter 3, we show that suppliers clustering can reduce the solution cost at the medium frequency range; while at the low and high frequency range, the cost saving is less. Demand variations can affect the cost of the solution by shifting the solution curve toward or away from the axis. Demand often depends on the seasons of the year, especially during a car's model change. Vehicle capacity is important at low frequency range, but creates negligible effect at high frequency range. This is because at high frequency, there are more visits that can use up all the time windows. Load distribution does not matter much in CFR. The null effect indicates that the routes are capable of sharing the loads in almost all situations.

In chapter 4, a one-supplier, one-part source, JSS model is created in ARENA / SIMAN. The model shows that the system's inventory level tends to be sticky to the reordering level. Overall, JSS is very stable, but it requires reliable transportations to perform well. When a supplier is unreliable (i.e. the supplier's lead time is variable), the inventory level is not affected. On the other hand, when the shipment arrivals time is unstable, the inventory level becomes unstable, to such an extent that it is harder to set a low reordering level.

We also demonstrate the effect of changeover in the system due to an increase in the demand. The impact to inventory level from changeover is relatively long term and only dampens out after several waves of fluctuations in the inventory level. To counter this effect, gradual change in the number of kanban cards is introduced, as well as an early route change. An early route change is required to accommodate the increase in capacity.

Finally, a scatter-search algorithm is used to solve the vehicle routing problem with time window (VRPTW). The result is shown in Appendix B.

5.2 Limitations

As it is, JSS can apply to large manufacturers only where there are many part sources. Applying the system is difficult as there are not many part sources to share. One possible solution is for companies to cooperate in handling their inbound shipments. It requires co-locating the companies and a dedicated carrier company.

Although the GFR algorithm is functional, it is not very efficient. Additional procedure needs to be added to deal with the handling of pickups. It is hard to justify its use since the cost advantage of GFR over CFR is small, especially when the algorithm is weak.

5.3 Future Research

We have defined the overall structure of JSS, but there are still several areas that we can improve, as follow:

1. Create a better algorithm that more resembles GFR, but still contains the simplistist feature in CFR.

2. Study the plant to plant sharing of load pickup with cross-docking facilities in details. We believe that there are some important advantages for having cross-docking facilities.
3. Study the methods of reducing the planning cycle. The planning cycle in the current system is limiting the ability of the system to respond to changes in demands quickly.
4. Simulate internal conveyance in more details.
5. Model a more detail simulation system that includes multiple suppliers, multiple part sources, and multiple routes.

5.4 Implications and Discussions

In the discussions during the final exam, the committee feels that route optimization and supply pickup and delivery system are all very important, not only to manufacturing, but to building construction and biosystem as well. Whether the current problem can be expanded to these systems depends on the requirements of each problem and the model approach. It is discussed that due to the specificity of the problems that scale modeling does not apply.

JSS's future is in supply chain integration. A global coordination of parts distribution holds much more savings in production cost, through sharing of parts deliveries and balancing production volumes at different manufacturing plants. With advanced computer technology, it is possible to package car designs and manufacturing processes into computer files such that they can be used quickly reconfigure a plant for new production. With such a technology, the logistics system should also improve hand-in-hand with the production system, such that parts are delivered to the right plant at the right time.

Another possibility for the future is the extension of the system to second-tier suppliers or the product distribution channels. Similar saving can be achieved if second-tier suppliers apply lean production in handling parts to their respective first-tier suppliers. With this type of integration, saving in production and logistics will pass along the supply chain system to the manufacturers and the consumers; it is a win-win solution. Today's customers demand high quality products and prompt shipments. Electronic communication and computers have enabled people to order the parts just-in-time (JIT) and track them over the globe. The internet will play a major role in this integration as software replaces hardware; information replaces materials; and electrons replace papers.

An added factor in this new market is the environment. As people become satisfied with the products, they start demanding environmentally friendly products. It is natural to support and buy from companies that serve and protect the community's natural resources, as the industry matured. Nevertheless, the environmental issues serve a higher-level of needs and can never replace the lower-level needs such as the price and performance. If a company can barely satisfy the lower-level needs, the environmental protection agencies may put it out of business. Thus, investing in environment will become a competitive advantage.

From the lean manufacturing point of view, the process is cutting waste. Sometimes it is self-discipline; sometimes it is because of competition. Although lean manufacturing has been in the fore front of manufacturing system development, it will also soon take a back seat, being absorbed into the coporate culture. Though the principles still hold true, but the practice will evolve. There are new tools that extend the kanban (such as Conwip, e-kanban), pull production (such as hybrid push and pull), visual management (such as electronics), and one-piece-flow (such as cellular). Yet, we know that the tool does not matter. The idea has always been the determination of the people to work inside the system, to catch the errors, to mind the small stuff, to never compromise the quality, to be flexible, and to adapt.

Hence from the big picture flexible system such as the JSS needs to evolve efficiently and improves itself through self-correction. Once in a while it takes a wrong path; but then, it recovers. A dynamic system that changes everyday is hard for the competitors to steal. Regardless of the competitors, the best enemy for a system is its own stagnation, as in long term repetition.

Appendix A: Dissertation A3

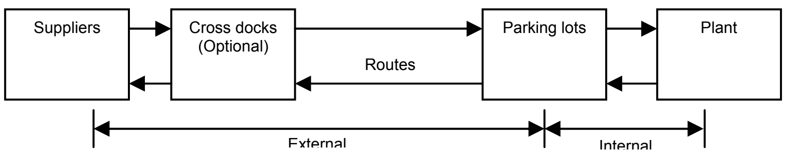
Name: Keng Hoo Chuah
Group: Lean Manufacturing
Date: 06/20/2003

Optimizations and Simulations of General Frequency Routing for Just-in-time Supply Pickup and Delivery Systems

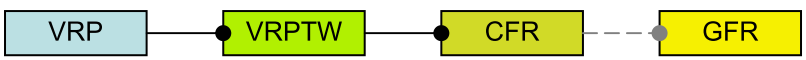
Abstract

This research studies three aspects of the just-in-time (JIT) pickup and delivery system (JSS) and combinatorial problems in general. First, a new meta-heuristics approach is developed to solve the general frequency routing (GFR) of the JIT supply pickup and delivery system. The approach uses features of taboo search (TS) in combination under a unified framework. Second, a discrete event simulation model is being developed to study the stability of the JSS system. Finally, four characteristics of common frequency routing problem are being explored to understand its impact on external conveyance.

Background:
A JIT supply pickup and delivery system manages the logistic operations between a central JIT manufacturing plant and its suppliers. The system controls the sequence, timing, and frequency of pickups and deliveries of parts and empty containers. In practice, the system has to be divided into internal conveyance and external conveyance, due to complexity. Cross-docking facilities may subdivide the external conveyance further if needed.



General Frequency Routing



General frequency routing (GFR) belongs to a class of problems called *vehicle routing problem* (VRP). VRP defines the problem of minimizing the cost of parts transport between a depot and the suppliers in round trip routes that start and end at the depot. In the literature, VRP has been expanded to include time windows and load constraints called *vehicle routing problem with time window* (VRPTW). In my master thesis, we study routing with pickup frequencies and a total transport space constraint. We name the problem *common frequency routing* (CFR). CFR is a simplification of the real problem, GFR. Under CFR we only consider routing designs where each part source is being served by a single route run at fixed daily frequency instead of designs where multiple routes visit that supplier each potentially run at a different frequency. In general frequency routing (GFR), all supplier pickup frequencies are independent of the route pickup frequency. Thus, a route in GFR has the options to visit a partial set of the suppliers covered by the route. The complexity created by this feature prohibits use of the column generation approach as outlined in the literature since routing by simply prescribing the first route of the cycle is no longer viable. A generalized meta-heuristics approach overcomes the complexity of GFR by making an extensive used of adaptive memory in a systematic manner.

GFR mathematical formulation:
The objective of GFR is to minimize the transportation cost and the transport space cost. There are five types of constraints: flow, space, load, time, and heijunka. The flow constraints are similar as before except for the addition of the supplier pickup frequency. The space constraints define the allocation of transport space to the suppliers on the route. The load and time constraints are similar to that of VRPTW. The heijunka constraints level the supplier pickup volume by restricting the visiting time to the suppliers.

Cross-dock Routing

JSS uses cross-dock facilities if the situation permits. Cross-docking facilities placed in some regions can improve shipping and handling of overly complex routes. A cross-dock routing (CDR) formulation for CFR is developed. In the formulation, the status of the suppliers is not defined prior to optimization. A supplier can become a cross-dock supplier or a direct supplier. It is assumed that the sub routes are performed ahead of the main routes. Hence, when a main route visits a cross docking facility, the parts have already reached the facility.

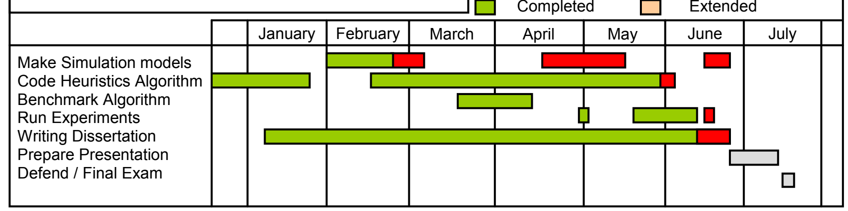
Effects of common frequency routing

The studies of JSS structural features on the operating costs of JSS systems under the assumption of CFR routes yielded interesting results. First, when suppliers are clustered, the routes become more efficient at mid-level, but not high or low, frequencies. Second, the cost increases with the number of suppliers. Third, negotiating broad time windows with suppliers is important for cost control in JSS systems. Fourth, an increase or decrease in production volumes uniformly shifts the solutions' cost versus frequency curve. Fifth, increased vehicle capacity is important in reducing costs at low and medium frequencies but far less important at high frequencies. Lastly, load distributions among the suppliers are not important determinants of transportation costs as long as the average loads remain the same.

Simulation of Stability of JSS

Simulation modeling technique is used to analyze complex system's performance when analytical approach is insufficient while full-scale experiment is too expensive. The objective of this simulation is to study the stability of a Just-in-time Supply Pickup and Delivery System (JSS) in managing inventory supply with the supplier Kanban system. Although JSS controls neither the Kanban system nor the parts reordering, JSS planning indirectly affects these systems through routing. Parts are scheduled in the JSS based on forecast of the total vehicle order (TVO) and the current inventory level. Since parts are produced to order, inventory is automatically capped over a production cycle. Nevertheless, short-term policy in maintaining the inventory supply may create inefficiency, or in the case of stock out, halt the production.

Schedule & Plan



This research would not be possible without the helps and supports from Toyota Motors Manufacturing, Kentucky, Toyota Fellows Program, Center for Robotics and Manufacturing System, Dr. Kozo Saito, Dr. Jon Yingling, all my committee members, and IAES members.

Appendix B: Meta-heuristics

B.1 Overview

A heuristic is an algorithm that solves a problem by repeatedly guessing. A problem may have no feasible solution or many optimum solutions. The steps are, first, to find a feasible solution; then, to improve the feasible solution according to an objective function. Whether a solution is feasible or not, they are all defined in a search space. The larger the search space, the harder it is to find the optimum solution. In the literature, the performance of heuristics depends on tweaking the algorithm and exploiting the structure of the problem; one wins by making the finest guess. Some methods work well, but not in all cases.

Heuristics usually solve combinatorial problems. In these problems, the best values of the variables cannot be determined independently but together as a set. Consequently, the search space of a combinatorial problem increases exponentially to the size of the problem, denoted N. Some combinatorial problems are easy to solve, while others are a mystery. Problems that can be solved in a number of steps bounded by a polynomial function of N are designated P. Problems that their solutions can be verified in the same manner (that is in a number of steps bounded by a polynomial function of N) are designated NP. All P problems are NP, but all NP problems may or may not be P.

Heuristics have developed into meta-heuristics, made possible by faster computers. Meta-heuristics usually combine several heuristics, track multiple solutions, and mimic the behavior of natural phenomena in their search strategies. Genetic Algorithms (GA), Taboo Search (TS), Ant Colonies Optimization (ACO), Iterative Local Search (ILS), and Simulated Annealing (SA) are some of the popular meta-heuristics. GA has become part of evolutionary computing (EC), which includes neural networks and artificial intelligence.

B.2 Taboo Search and VRP

Taboo search (TS) is a meta-heuristics algorithm that exploits a neighborhood search with a historical tracking list that guides the solution out of local optimum points. Taboo search starts with an initial solution, and performs a neighborhood search to find a new solution. To be a new solution, it must be absent from the tracking list since such solutions are deemed "taboo". This simple mechanism is generally effective in preventing convergence to local optimums. If the new solution is feasible, it is compared with the best solution in the algorithm. If it beats the best solution, it becomes the best solution. The algorithm then records this new solution into the tracking list, and performs another neighborhood search with this new solution. It repeats until one or more of the termination conditions are satisfied. Termination conditions are the maximum number of iterations or the maximum number of iterations with no improvement to the best solution. Note that the number of solutions in the tracking list is limited. Therefore, some solutions in the list are dropped after a number of iteration, normally after the taboo period expires.

In applying taboo search to VRP-type problems, the neighborhood is defined in terms of the routes in the current solution. A search of the neighborhood enumerates candidate solution obtained by exchanging a number of nodes on a pair of routes. Specifically, we applied the CROSS exchange technique developed by Taillard and Badeau (1997), which is a generalization of the 2-exchange and the Or-exchange. In a standard routing problem, a complete CROSS exchange neighborhood can be generated in $O(n^4)$ time where n is the number of vertices. In CFR, the time is $O(n^4 + f^2)$ to account for the frequencies. Fortunately, the range of frequency is small. The CROSS exchange technique is computationally more expensive than the 2-exchange and the Or-exchange, but algorithms that use this technique have been shown to produce better candidate solutions than using either technique independently (Taillard and Badeau, 1997). Since a complete enumeration is expensive, we also consider a partial enumeration during regular iteration, and reserve the full enumeration for the intensification process.

B.3 Scatter Search and VRP

The idea of scatter search (SS) is to combine good solutions with diverse solutions to penetrate local regions of the search space. A solution is diverse when it is far from the good solutions, according to a distance function. The process of mixing the solutions is very similar to the cross over function in genetic algorithm (GA). Nevertheless, instead of binary mixing, SS applies a linear combination of two or more solutions. The final solution is derived using a certain acceptance and rejection criterion.

SS cannot function alone because in most cases, generated solutions are not efficient. SS needs another local search algorithm, like the taboo search, to optimize these generated solutions with local neighborhood search.

In applying SS to VRP-type problems, it is not necessary to use an entire solution as the basis for finding the good solutions or the diverse solutions. It is also possible to use the routes in the solutions as the basis, such as good routes and diverse routes. Then, combining solutions amounts to mixing different routes together. After that, a new solution is generated from the combined routes.

B.4 Ant Colony Optimization and VRP

Ant colony optimization (ACO), proposed in the early 1990s, simulates the ants' foraging behavior as a search algorithm (Dorigo and Di Caro, 1999). The key idea is the pheromone trails that ants leave behind when they search for food. The pheromone can be utilized as a form of optimization routine. If the trails help the ants to coordinate their search efficiently, perhaps it will help us search for good transportation solutions.

ACO is fundamentally different from TS in that it conducts neighborhood search by building complete solutions. Once a solution is built, ACO does not improve it any further. Instead, another solution is built based on the traces (pheromone) from the previous solution.

ACO compliments TS very well. TS conducts neighborhood search by improving an existing solution. The first solution of TS is an initial solution, built by a simple heuristic algorithm. Rather than using simple heuristic, TS is embedded within the ACO framework, such that for every solution built by ACO, an improved solution is generated by TS. After that, the improved solution is applied to the pheromone graph.

The pheromone graph is actually values on the arcs of the graph, specifying the desirability of these arcs in relation to one another. For VRP-type problems, we found that, in general, the solutions generated by ACO by itself are not efficient. A local search algorithm, such as TS, is usually required.

B.5 Unified Framework

Taillard et al. proposed for a unified view of meta-heuristics under the name Adaptive Memory Programming (AMP) (Taillard et al., 2001). Their paper reviews a number of combinatorial problems (quadratic assignment, vehicle routing, and graph coloring problems) and commonly applied meta-heuristics from AMP perspective. The paper is insightful and we extend the proposal into more concrete theory. In this section, we define the block structure of meta-heuristics.

A generalized meta-heuristics should have at least two blocks: a building algorithm and a local search algorithm. The building algorithm sequentially builds a solution out of a problem with the use of some memory (tracing) structure. The memory structure is usually global in nature, able to be applied to the algorithm's building process at any stage. It can be a solution to the problem or a matrix of probabilities. It can be a feasible or infeasible solution. It can be a complete or incomplete solution. Deciding on which depends on the complexity and characteristics of the problem at hand. One property of the memory structure is that it can be constructed into a real solution through a straightforward transformation.

The first objective of the building algorithm is to identify the memory structure that best represents the potential of all regions in the search space. Since the memory structure can reconstruct the best solutions, it can also recall other key solutions. A memory structure, however, does not necessary represent only the best solutions. One example of a memory structure is from SS, where there are both elite solutions and diverse solutions. Another example is the ants' pheromone trail from ACO. The GA's "population" is also another form of memory structure.

The second objective of the building algorithm is to identify the various stages of the search process. There are three stages in the algorithms, the beginning stage, the middle stage, and the end stage. Heuristics algorithms usually converge quickly to a local optimum at some points in the beginning stage. This is also the termination criterion of simple heuristics. More advanced heuristics go into the middle stage by jumping out of the local optimum points. To perform this operation, an algorithm records its search in some forms of data structure using the features of the problem. Since TS records previously generated solutions, it is at least a second stage algorithm. Not many heuristics get to the end stage, except for the brute force (exhaustive search) approach, which is not a meta-heuristics method. The end stage indicates that most regions of the search space have been explored thoroughly and systematically. To satisfy the second objective, a building algorithm monitors and directs the search algorithm systematically through building of unexplored solutions.

A local search algorithm explores a region of the search space while jumping in and out of local optimum points. They are meta-heuristics that perform detail and sometime exhaustive search of a neighborhood, given an initial solution to that neighborhood. A building algorithm assists by providing the initial solution.

Figure B.1 below shows the generalized meta-heuristics.

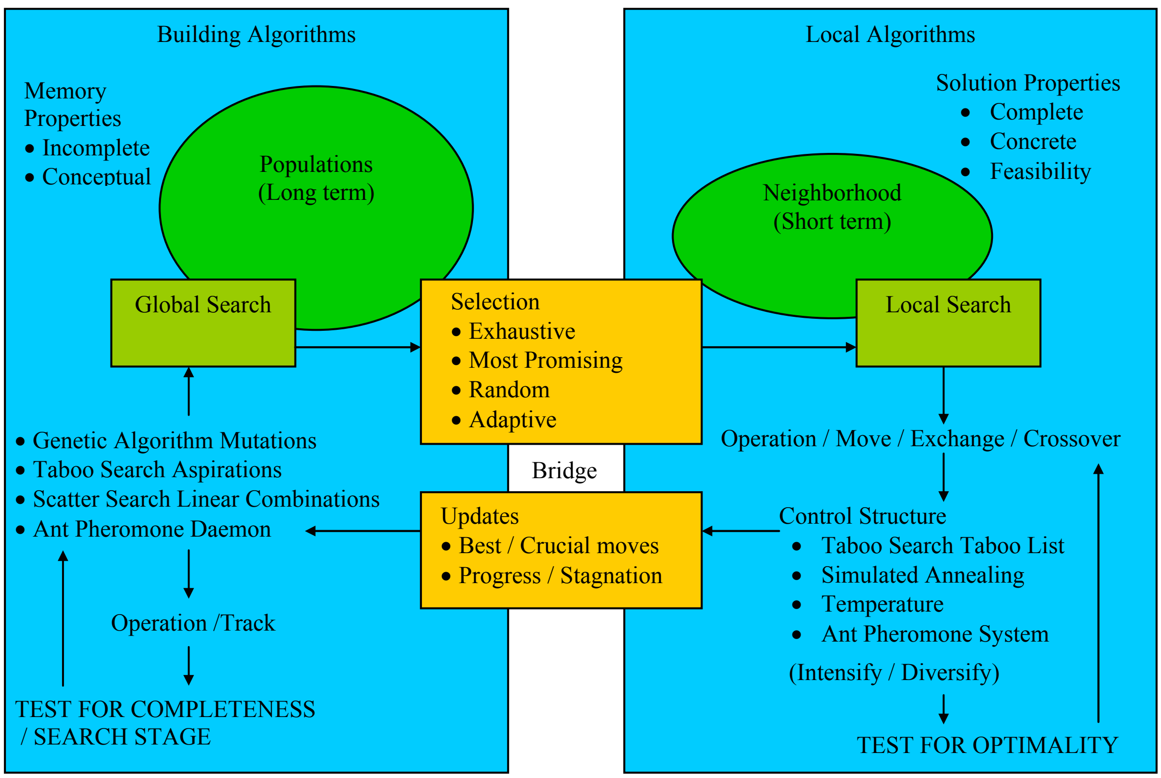


Figure B.1: Generalized Meta Heuristics

B.6 Advanced Structures

It is possible to stack the local search algorithms within one another, since they are meta-heuristics. Furthermore, multiple building algorithms, multiple search algorithms in a nested framework, and cooperating search algorithms should all be possible. In a nested framework, the inner algorithm contains another algorithm. Multiple frameworks may cooperate in defining the best representation of the search space, where each framework uses a different solution structure. Such a framework is probably useful in solving very complex problems.

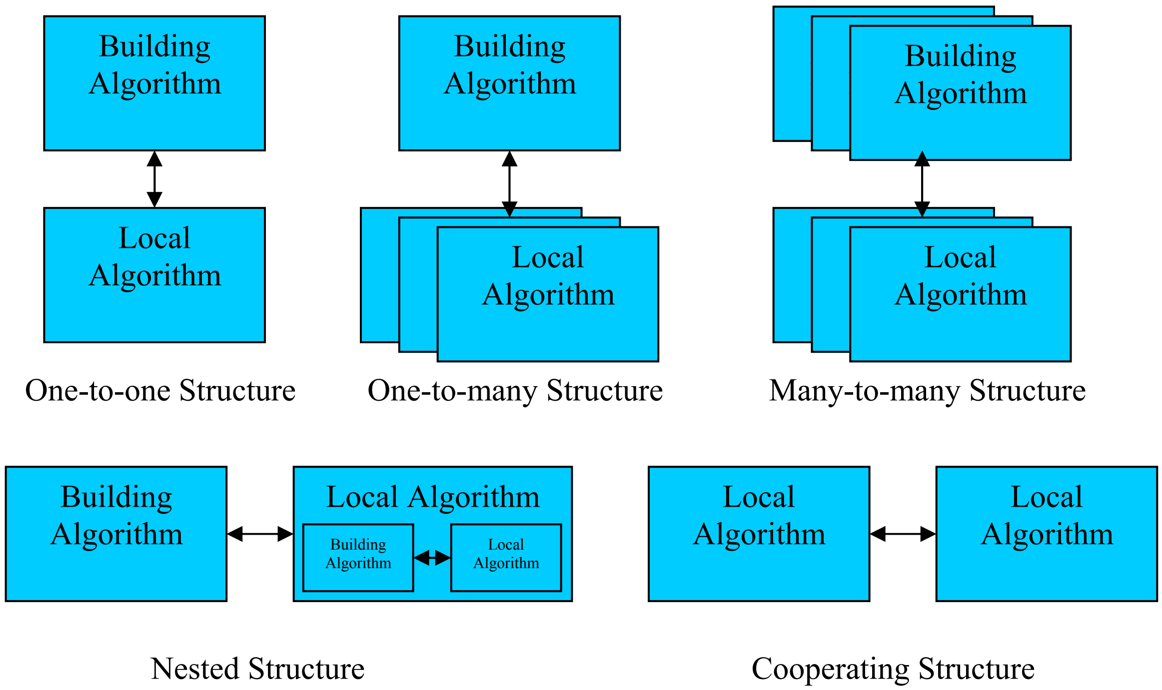


Figure B.2: Advanced Structures

Suppose an algorithm is as efficient as theoretically possible. What is left is the issue of processing time. In practice, we cannot change the problem. Complex problems demand fast processors, instead of simplification. Simplification is just one way to compensate for lack of processing power, but then we never really solve the real problem.

Using object-oriented programming, a specialization of the components in the building algorithm-local algorithm framework allows us to create different meta-heuristic algorithms as if they are a common structure. With common structures, the algorithms are combined as building blocks to form algorithms that are more powerful. The next three figures illustrate our approach.

Figure B.3: Diagram Showing an Object-oriented Implementation of Meta-heuristic

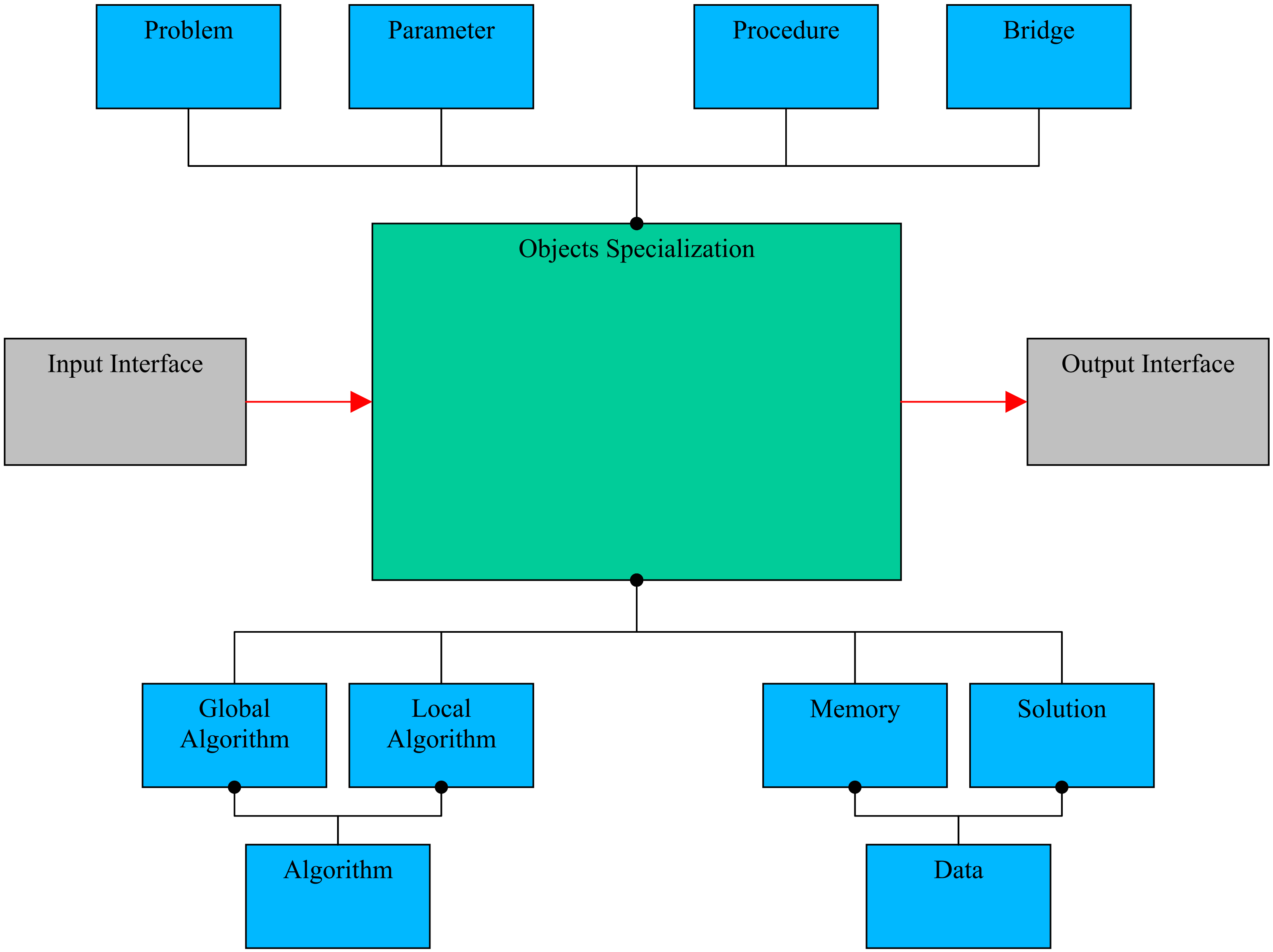


Figure B.4: Diagram of Building Vehicle Routing Problem with Scatter Taboo Search

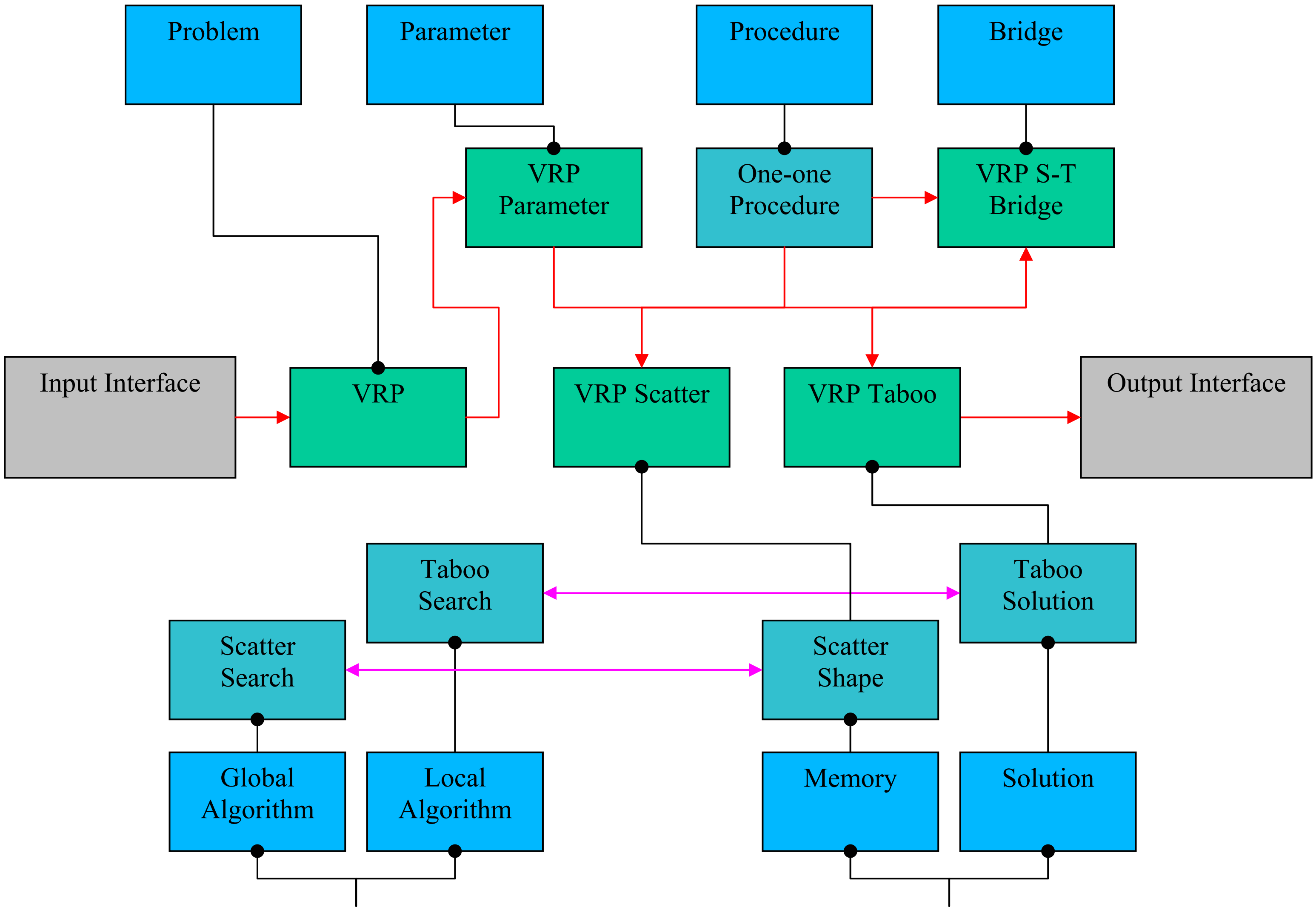
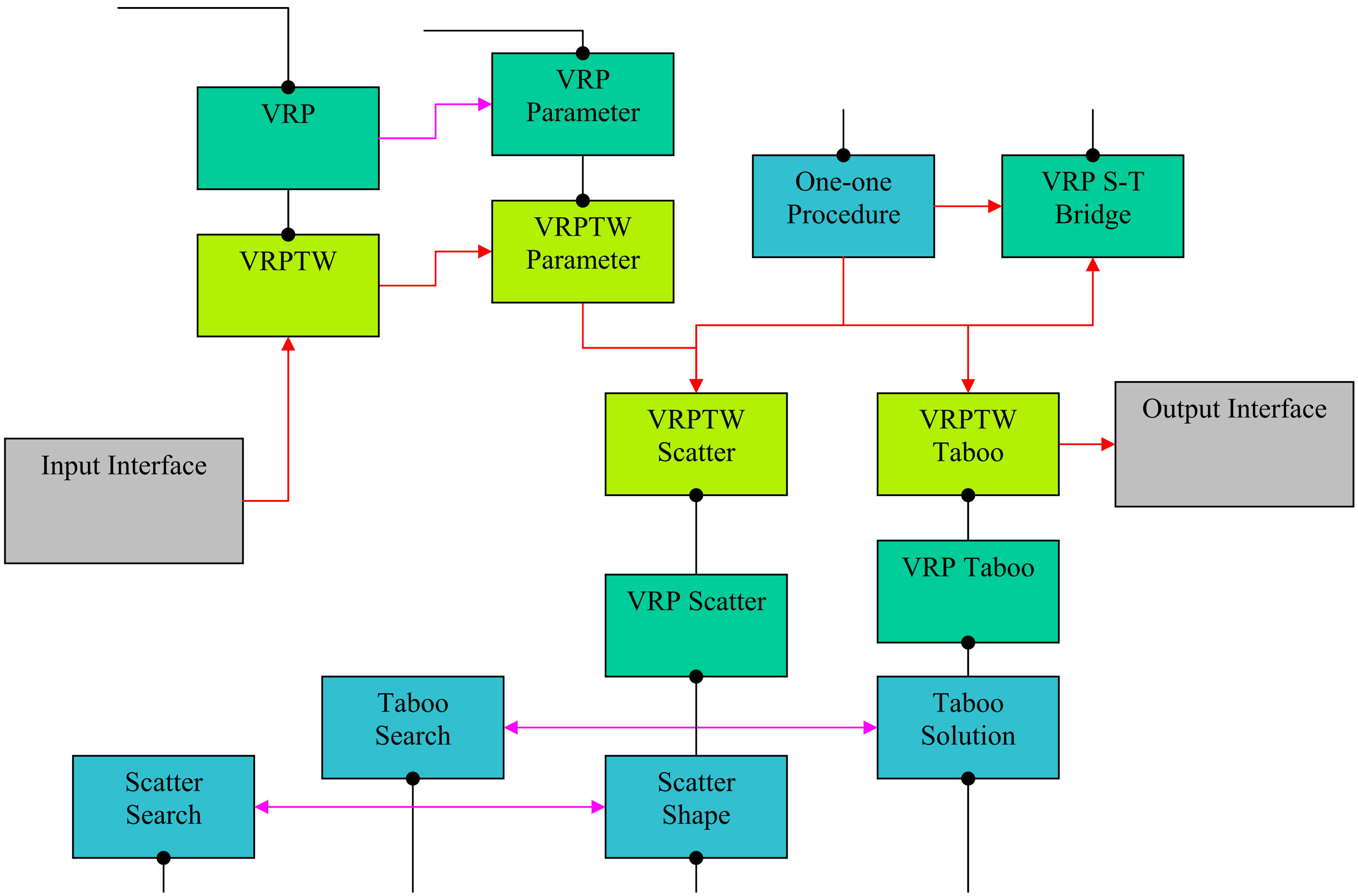


Figure B.5: Diagram of Adding Time Window to Vehicle Routing Problem



B.7 VRPTW Benchmark Results

This benchmark is a set of twelve randomly generated problems (R series) generated by Solomon and available in the literature (Solomon, 1986; Solomon, 1987). Figure B.6 below shows a header section of a VRPTW problem.

```
R101

VEHICLE
NUMBER     CAPACITY
  25         200

CUSTOMER
CUST NO.   XCOORD.   YCOORD.    DEMAND   READY TIME   DUE DATE   SERVICE TIME

    0         35        35          0        0          230           0
    1         41        49         10      161          171          10
    2         35        17          7       50           60          10
    3         55        45         13      116          126          10
    4         55        20         19      149          159          10
    5         15        30         26       34           44          10
    6         25        30          3       99          109          10
    7         20        50          5       81           91          10
    8         10        43          9       95          105          10
    9         55        60         16       97          107          10
   10         30        60         16      124          134          10
   11         20        65         12       67           77          10
```

Figure B.6: The Header Fragment of Problem R101

Three algorithms have been implemented in C++. They are taboo search, scatter taboo search, and ant taboo search. The complete solutions of the first problem for each algorithm are shown in Table B.1 below. The ant-taboo-search algorithm gives the best result, but spends more time on the search.

Figure B.7 below is a comparison of the average number of vehicles for all the R-series problems. The data for other algorithms is obtained from Gambardella et al. (1999) and (Tavares et al., 2002). On average, our algorithms require one extra vehicle to route since we did not put enough emphasis on vehicle reduction.

Table B.1: Best R101 Solutions given by Different Algorithms

TABU SEARCH	SCATTER-TABU SEARCH	ANT-TABU SEARCH
ROUTE: 0-65-71-9-66-1-0	ROUTE: 0-2-21-73-41-56-4-0	ROUTE: 0-27-69-30-51-20-32-70-0
ROUTE: 0-5-61-85-37-93-0	ROUTE: 0-5-83-61-85-97-13-0	ROUTE: 0-92-42-15-87-57-97-0
ROUTE: 0-52-18-6-0	ROUTE: 0-6-0	ROUTE: 0-31-88-7-0
ROUTE: 0-21-73-26-0	ROUTE: 0-14-44-38-43-91-100-0	ROUTE: 0-59-99-94-96-0
ROUTE: 0-27-69-30-51-20-32-70-0	ROUTE: 0-27-69-51-9-66-1-0	ROUTE: 0-45-82-18-84-60-89-0
ROUTE: 0-33-81-50-68-0	ROUTE: 0-28-12-76-79-3-68-0	ROUTE: 0-36-47-19-8-46-17-0
ROUTE: 0-82-8-46-0	ROUTE: 0-31-30-20-32-70-0	ROUTE: 0-14-44-38-43-13-0
ROUTE: 0-36-47-19-0	ROUTE: 0-33-29-78-34-35-77-0	ROUTE: 0-5-83-61-85-37-93-0
ROUTE: 0-39-23-67-55-25-0	ROUTE: 0-36-47-19-8-46-17-0	ROUTE: 0-33-81-50-0
ROUTE: 0-59-99-94-96-0	ROUTE: 0-39-23-67-55-25-0	ROUTE: 0-52-6-0
ROUTE: 0-40-53-0	ROUTE: 0-40-53-26-0	ROUTE: 0-63-64-49-48-0
ROUTE: 0-45-83-84-60-89-0	ROUTE: 0-45-82-18-84-60-89-0	ROUTE: 0-72-75-22-54-24-80-0
ROUTE: 0-63-64-49-48-0	ROUTE: 0-52-88-7-0	ROUTE: 0-12-76-79-3-68-0
ROUTE: 0-95-98-16-86-17-0	ROUTE: 0-59-99-94-96-0	ROUTE: 0-95-98-16-86-91-100-0
ROUTE: 0-62-11-90-10-0	ROUTE: 0-62-11-90-10-0	ROUTE: 0-28-29-78-34-35-77-0
ROUTE: 0-72-75-22-74-58-0	ROUTE: 0-63-64-49-48-0	ROUTE: 0-39-23-67-55-4-25-0
ROUTE: 0-28-29-78-34-35-77-0	ROUTE: 0-65-71-81-50-0	ROUTE: 0-2-21-73-41-56-74-58-0
ROUTE: 0-12-76-79-3-54-24-80-0	ROUTE: 0-72-75-22-54-24-80-0	ROUTE: 0-65-71-9-66-1-0
ROUTE: 0-31-88-7-0	ROUTE: 0-92-42-15-87-57-74-58-0	ROUTE: 0-62-11-90-10-0
ROUTE: 0-2-87-57-97-13-0	ROUTE: 0-95-98-16-86-37-93-0	ROUTE: 0-40-53-26-0
ROUTE: 0-92-42-15-41-56-4-0		
ROUTE: 0-14-44-38-43-91-100-0		
COST: 1674.88 VEHICLES: 22	COST: 1655.16 VEHICLES: 20	COST: 1645.84 VEHICLES: 20
TIME: 23.424	TIME: 83.5	TIME: 100.474

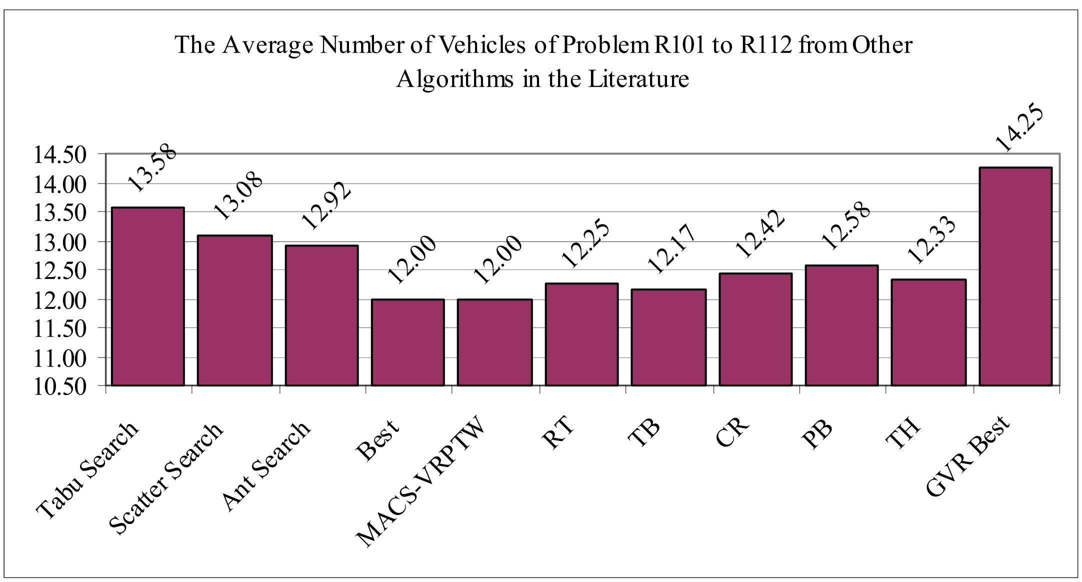


Figure B.7: A Comparison of Average Number of Vehicles from Different Algorithms

Figure B.8 below is a comparison of the average travel distance for all the R-series problems. Except for taboo search, our algorithms perform quite well in the search.

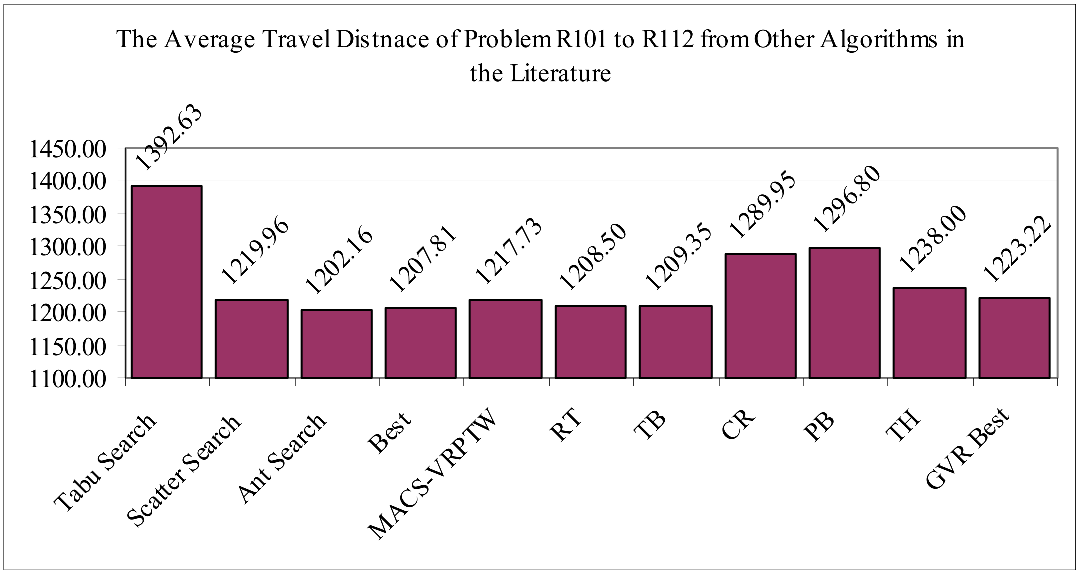


Figure B.8: A Comparison of Average Travel Distance from Different Algorithms

Appendix C: Problems

This appendix contains the input files and the input parameters for a number of problems referenced in this dissertation.

C.1 Problem R1

Table C.1: Problem R1

```
Begin Route
1 Capacity Frequency Speed Vehicle
50 12 1 100
End Route
Begin Supplier
101 Code Docks Start End Break Stop Pallets Round Weight L W H
90000 00 00 0 3500 0 0 0 1 1 0 0 0    1 XX 00 685 2289 0 25 78 1 1 48 48 48    2 XX 00 701 2193 0 25 99 1 1 48 48 48
3 XX 00 744 1673 0 25 68 1 1 48 48 48    4 XX 00 786 1818 0 25 45 1 1 48 48 48    5 XX 00 752 1869 0 25 16 1 1 48 48 48
6 XX 00 634 1593 0 25 53 1 1 48 48 48    7 XX 00 721 1581 0 25 93 1 1 48 48 48    8 XX 00 682 1630 0 25 89 1 1 48 48 48
9 XX 00 626 2261 0 25 18 1 1 48 48 48    10 XX 00 795 1700 0 25 41 1 1 48 48 48    11 XX 00 740 2222 0 25 41 1 1 48 48 48
12 XX 00 779 1836 0 25 24 1 1 48 48 48    13 XX 00 657 1938 0 25 23 1 1 48 48 48    14 XX 00 687 1961 0 25 61 1 1 48 48 48
15 XX 00 642 1681 0 25 25 1 1 48 48 48    16 XX 00 712 1763 0 25 89 1 1 48 48 48    17 XX 00 776 2184 0 25 49 1 1 48 48 48
18 XX 00 635 1992 0 25 36 1 1 48 48 48    19 XX 00 649 1798 0 25 51 1 1 48 48 48    20 XX 00 765 2120 0 25 99 1 1 48 48 48
21 XX 00 624 2226 0 25 31 1 1 48 48 48    22 XX 00 752 2237 0 25 33 1 1 48 48 48    23 XX 00 657 2167 0 25 59 1 1 48 48 48
24 XX 00 643 1622 0 25 29 1 1 48 48 48    25 XX 00 694 2278 0 25 61 1 1 48 48 48    26 XX 00 774 2299 0 25 63 1 1 48 48 48
27 XX 00 616 1831 0 25 19 1 1 48 48 48    28 XX 00 777 1640 0 25 94 1 1 48 48 48    29 XX 00 766 2148 0 25 95 1 1 48 48 48
30 XX 00 713 2145 0 25 12 1 1 48 48 48    31 XX 00 756 2142 0 25 82 1 1 48 48 48    32 XX 00 777 1834 0 25 98 1 1 48 48 48
33 XX 00 650 1916 0 25 22 1 1 48 48 48    34 XX 00 617 2126 0 25 59 1 1 48 48 48    35 XX 00 683 2250 0 25 53 1 1 48 48 48
36 XX 00 759 2171 0 25 38 1 1 48 48 48    37 XX 00 705 1916 0 25 42 1 1 48 48 48    38 XX 00 791 2221 0 25 84 1 1 48 48 48
39 XX 00 705 1517 0 25 96 1 1 48 48 48    40 XX 00 753 2277 0 25 49 1 1 48 48 48    41 XX 00 752 2138 0 25 97 1 1 48 48 48
42 XX 00 754 2051 0 25 21 1 1 48 48 48    43 XX 00 624 1915 0 25 24 1 1 48 48 48    44 XX 00 726 1514 0 25 49 1 1 48 48 48
45 XX 00 657 2297 0 25 18 1 1 48 48 48    46 XX 00 696 2061 0 25 33 1 1 48 48 48    47 XX 00 738 2288 0 25 94 1 1 48 48 48
48 XX 00 622 1954 0 25 34 1 1 48 48 48    49 XX 00 791 1858 0 25 11 1 1 48 48 48    50 XX 00 718 1824 0 25 26 1 1 48 48 48
51 XX 00 700 1554 0 25 15 1 1 48 48 48    52 XX 00 755 1616 0 25 57 1 1 48 48 48    53 XX 00 647 2079 0 25 21 1 1 48 48 48
54 XX 00 796 2265 0 25 83 1 1 48 48 48    55 XX 00 773 1923 0 25 88 1 1 48 48 48    56 XX 00 755 1762 0 25 15 1 1 48 48 48
57 XX 00 621 2173 0 25 92 1 1 48 48 48    58 XX 00 772 2159 0 25 80 1 1 48 48 48    59 XX 00 735 1998 0 25 14 1 1 48 48 48
60 XX 00 603 1995 0 25 76 1 1 48 48 48    61 XX 00 642 2023 0 25 18 1 1 48 48 48    62 XX 00 712 2089 0 25 42 1 1 48 48 48
63 XX 00 759 2047 0 25 98 1 1 48 48 48    64 XX 00 765 2169 0 25 85 1 1 48 48 48    65 XX 00 651 1973 0 25 22 1 1 48 48 48
66 XX 00 715 2237 0 25 77 1 1 48 48 48    67 XX 00 730 1712 0 25 25 1 1 48 48 48    68 XX 00 742 1658 0 25 31 1 1 48 48 48
69 XX 00 614 1725 0 25 40 1 1 48 48 48    70 XX 00 740 1585 0 25 67 1 1 48 48 48    71 XX 00 739 2026 0 25 22 1 1 48 48 48
72 XX 00 663 2179 0 25 84 1 1 48 48 48    73 XX 00 675 1651 0 25 85 1 1 48 48 48    74 XX 00 714 1696 0 25 31 1 1 48 48 48
75 XX 00 785 1632 0 25 49 1 1 48 48 48    76 XX 00 628 1526 0 25 57 1 1 48 48 48    77 XX 00 729 2176 0 25 55 1 1 48 48 48
78 XX 00 697 1853 0 25 92 1 1 48 48 48    79 XX 00 648 2251 0 25 96 1 1 48 48 48    80 XX 00 634 2009 0 25 29 1 1 48 48 48
81 XX 00 621 2113 0 25 33 1 1 48 48 48    82 XX 00 767 1534 0 25 48 1 1 48 48 48    83 XX 00 759 2100 0 25 40 1 1 48 48 48
84 XX 00 788 1755 0 25 83 1 1 48 48 48    85 XX 00 657 2023 0 25 79 1 1 48 48 48    86 XX 00 794 1789 0 25 87 1 1 48 48 48
87 XX 00 626 1921 0 25 66 1 1 48 48 48    88 XX 00 639 2260 0 25 22 1 1 48 48 48    89 XX 00 622 2283 0 25 85 1 1 48 48 48
90 XX 00 782 1504 0 25 50 1 1 48 48 48    91 XX 00 648 2297 0 25 94 1 1 48 48 48    92 XX 00 736 1958 0 25 55 1 1 48 48 48
93 XX 00 605 1923 0 25 78 1 1 48 48 48    94 XX 00 728 1725 0 25 40 1 1 48 48 48    95 XX 00 666 1732 0 25 37 1 1 48 48 48
96 XX 00 643 1987 0 25 78 1 1 48 48 48    97 XX 00 615 1518 0 25 82 1 1 48 48 48    98 XX 00 688 2008 0 25 36 1 1 48 48 48
99 XX 00 694 2175 0 25 57 1 1 48 48 48    100 XX 00 714 1925 0 25 85 1 1 48 48 48
End Supplier
Begin Location
101 X Y
1000 1000    987 1230    821 131     557 1817    495 1246    1438 78
1725 1653    926 276     351 344     1038 491    1243 1886   159 254
1689 814     338 1561    1806 1511   1702 346    1654 43     1528 1286
1347 585     452 6       1732 1163   1309 1710   1551 559    464 158
442 1719     433 53      163 91      1437 1500   1065 1240   1361 1489
1553 104     1903 686    1093 1638   466 274     726 512     59 1578
1086 1379    233 916     951 68      185 1742    1636 1358   1878 57
221 1754     1577 1398   104 1422    1830 776    702 1166    1940 992
1840 1471    518 1979    383 324     175 581     1555 85     894 582
1104 338     501 1234    1548 598    1132 1165   144 1388    838 1610
```

Table C.1 (continued)

461 1577	939 782	1571 1427	1405 1923	1264 1627	1921 1627
530 74	460 476	141 1464	1431 1225	657 1110	1124 939
987 1205	347 852	1815 28	218 1580	1173 1788	213 1867
328 75	1066 614	1299 486	182 635	912 1215	1186 879
601 1435	1192 1739	483 1455	814 6	702 1118	1821 165
1029 978	1202 1287	1403 1749	1260 148	1735 504	617 1421
1198 485	1828 1362	1560 340	989 321	195 1405	
End Location					
Begin Param					
Vehicle_height 120		Vehicle_width 96		Far_far_away 10000000	
Vehicle_number 100		Inventory_number 10000		Alpha 10	
Beta 1		Inv_now 10		Max_columns 3000	
Min_distance 1		Weekly 1		Max_iteration 2000	
Max_load 25		Max_id 10000		Min_time 50	
TS_length 977		Max_freq 12		Min_time2 100	
Max_iter2 800					
End Param					

C.2 Problem R2

Table C.2: Problem R2

Begin Route		
1 Capacity Frequency Speed Vehicle		
50 12 1 100		
End Route		
Begin Supplier		
101 Code Docks Start End Break Stop Pallets Round Weight L W H		
90000 00 00 0 3500 0 0 0 1 1 0 0 0	1 XX 00 685 2289 0 25 57 1 1 48 48 48	2 XX 00 701 2193 0 25 59 1 1 48 48 48
3 XX 00 744 1673 0 25 56 1 1 48 48 48	4 XX 00 786 1818 0 25 53 1 1 48 48 48	5 XX 00 752 1869 0 25 50 1 1 48 48 48
6 XX 00 634 1593 0 25 54 1 1 48 48 48	7 XX 00 721 1581 0 25 59 1 1 48 48 48	8 XX 00 682 1630 0 25 58 1 1 48 48 48
9 XX 00 626 2261 0 25 50 1 1 48 48 48	10 XX 00 795 1700 0 25 53 1 1 48 48 48	11 XX 00 740 2222 0 25 53 1 1 48 48 48
12 XX 00 779 1836 0 25 51 1 1 48 48 48	13 XX 00 657 1938 0 25 51 1 1 48 48 48	14 XX 00 687 1961 0 25 55 1 1 48 48 48
15 XX 00 642 1681 0 25 51 1 1 48 48 48	16 XX 00 712 1763 0 25 58 1 1 48 48 48	17 XX 00 776 2184 0 25 54 1 1 48 48 48
18 XX 00 635 1992 0 25 52 1 1 48 48 48	19 XX 00 649 1798 0 25 54 1 1 48 48 48	20 XX 00 765 2120 0 25 59 1 1 48 48 48
21 XX 00 624 2226 0 25 52 1 1 48 48 48	22 XX 00 752 2237 0 25 52 1 1 48 48 48	23 XX 00 657 2167 0 25 55 1 1 48 48 48
24 XX 00 643 1622 0 25 52 1 1 48 48 48	25 XX 00 694 2278 0 25 55 1 1 48 48 48	26 XX 00 774 2299 0 25 55 1 1 48 48 48
27 XX 00 616 1831 0 25 51 1 1 48 48 48	28 XX 00 777 1640 0 25 59 1 1 48 48 48	29 XX 00 766 2148 0 25 59 1 1 48 48 48
30 XX 00 713 2145 0 25 50 1 1 48 48 48	31 XX 00 756 2142 0 25 58 1 1 48 48 48	32 XX 00 777 1834 0 25 59 1 1 48 48 48
33 XX 00 650 1916 0 25 51 1 1 48 48 48	34 XX 00 617 2126 0 25 55 1 1 48 48 48	35 XX 00 683 2250 0 25 54 1 1 48 48 48
36 XX 00 759 2171 0 25 53 1 1 48 48 48	37 XX 00 705 1916 0 25 53 1 1 48 48 48	38 XX 00 791 2221 0 25 58 1 1 48 48 48
39 XX 00 705 1517 0 25 59 1 1 48 48 48	40 XX 00 753 2277 0 25 54 1 1 48 48 48	41 XX 00 752 2138 0 25 59 1 1 48 48 48
42 XX 00 754 2051 0 25 51 1 1 48 48 48	43 XX 00 624 1915 0 25 51 1 1 48 48 48	44 XX 00 726 1514 0 25 54 1 1 48 48 48
45 XX 00 657 2297 0 25 50 1 1 48 48 48	46 XX 00 696 2061 0 25 52 1 1 48 48 48	47 XX 00 738 2288 0 25 59 1 1 48 48 48
48 XX 00 622 1954 0 25 52 1 1 48 48 48	49 XX 00 791 1858 0 25 50 1 1 48 48 48	50 XX 00 718 1824 0 25 51 1 1 48 48 48
51 XX 00 700 1554 0 25 50 1 1 48 48 48	52 XX 00 755 1616 0 25 55 1 1 48 48 48	53 XX 00 647 2079 0 25 51 1 1 48 48 48
54 XX 00 796 2265 0 25 58 1 1 48 48 48	55 XX 00 773 1923 0 25 58 1 1 48 48 48	56 XX 00 755 1762 0 25 50 1 1 48 48 48
57 XX 00 621 2173 0 25 59 1 1 48 48 48	58 XX 00 772 2159 0 25 57 1 1 48 48 48	59 XX 00 735 1998 0 25 50 1 1 48 48 48
60 XX 00 603 1995 0 25 57 1 1 48 48 48	61 XX 00 642 2023 0 25 50 1 1 48 48 48	62 XX 00 712 2089 0 25 53 1 1 48 48 48
63 XX 00 759 2047 0 25 59 1 1 48 48 48	64 XX 00 765 2169 0 25 58 1 1 48 48 48	65 XX 00 651 1973 0 25 51 1 1 48 48 48
66 XX 00 715 2237 0 25 57 1 1 48 48 48	67 XX 00 730 1712 0 25 51 1 1 48 48 48	68 XX 00 742 1658 0 25 52 1 1 48 48 48
69 XX 00 614 1725 0 25 53 1 1 48 48 48	70 XX 00 740 1585 0 25 56 1 1 48 48 48	71 XX 00 739 2026 0 25 51 1 1 48 48 48
72 XX 00 663 2179 0 25 58 1 1 48 48 48	73 XX 00 675 1651 0 25 58 1 1 48 48 48	74 XX 00 714 1696 0 25 52 1 1 48 48 48
75 XX 00 785 1632 0 25 54 1 1 48 48 48	76 XX 00 628 1526 0 25 55 1 1 48 48 48	77 XX 00 729 2176 0 25 55 1 1 48 48 48
78 XX 00 697 1853 0 25 59 1 1 48 48 48	79 XX 00 648 2251 0 25 59 1 1 48 48 48	80 XX 00 634 2009 0 25 52 1 1 48 48 48
81 XX 00 621 2113 0 25 52 1 1 48 48 48	82 XX 00 767 1534 0 25 54 1 1 48 48 48	83 XX 00 759 2100 0 25 53 1 1 48 48 48
84 XX 00 788 1755 0 25 58 1 1 48 48 48	85 XX 00 657 2023 0 25 57 1 1 48 48 48	86 XX 00 794 1789 0 25 58 1 1 48 48 48
87 XX 00 626 1921 0 25 56 1 1 48 48 48	88 XX 00 639 2260 0 25 51 1 1 48 48 48	89 XX 00 622 2283 0 25 58 1 1 48 48 48
90 XX 00 782 1504 0 25 54 1 1 48 48 48	91 XX 00 648 2297 0 25 59 1 1 48 48 48	92 XX 00 736 1958 0 25 55 1 1 48 48 48
93 XX 00 605 1923 0 25 57 1 1 48 48 48	94 XX 00 728 1725 0 25 53 1 1 48 48 48	95 XX 00 666 1732 0 25 53 1 1 48 48 48
96 XX 00 643 1987 0 25 57 1 1 48 48 48	97 XX 00 615 1518 0 25 58 1 1 48 48 48	98 XX 00 688 2008 0 25 52 1 1 48 48 48
99 XX 00 694 2175 0 25 55 1 1 48 48 48	100 XX 00 714 1925 0 25 58 1 1 48 48 48	

Table C.2 (continued)

End Supplier					
Begin Location	101 X Y				
1000 1000	987 1230	821 131	557 1817	495 1246	1438 78
1725 1653	926 276	351 344	1038 491	1243 1886	159 254
1689 814	338 1561	1806 1511	1702 346	1654 43	1528 1286
1347 585	452 6	1732 1163	1309 1710	1551 559	464 158
442 1719	433 53	163 91	1437 1500	1065 1240	1361 1489
1553 104	1903 686	1093 1638	466 274	726 512	59 1578
1086 1379	233 916	951 68	185 1742	1636 1358	1878 57
221 1754	1577 1398	104 1422	1830 776	702 1166	1940 992
1840 1471	518 1979	383 324	175 581	1555 85	894 582
1104 338	501 1234	1548 598	1132 1165	144 1388	838 1610
461 1577	939 782	1571 1427	1405 1923	1264 1627	1921 1627
530 74	460 476	141 1464	1431 1225	657 1110	1124 939
987 1205	347 852	1815 28	218 1580	1173 1788	213 1867
328 75	1066 614	1299 486	182 635	912 1215	1186 879
601 1435	1192 1739	483 1455	814 6	702 1118	1821 165
1029 978	1202 1287	1403 1749	1260 148	1735 504	617 1421
1198 485	1828 1362	1560 340	989 321	195 1405	
End Location					
Begin Param					
Vehicle_height 120		Vehicle_width 96		Far_far_away 10000000	
Vehicle_number 100		Inventory_number 10000		Alpha 10	
Beta 1		Inv_now 10		Max_columns 3000	
Min_distance 1		Weekly 1		Max_iteration 2000	
Max_load 25		Max_id 10000		Min_time 50	
TS_length 977		Max_freq 12		Min_time2 100	
Max_iter2 800					
End Param					

C.3 Problem R3

Table C.3: Problem R3

Begin Route		
1 Capacity Frequency Speed Vehicle		
50 12 1 100		
End Route		
Begin Supplier		
101 Code Docks Start End Break Stop Pallets Round Weight L W H		
90000 00 00 0 3500 0 0 0 1 1 0 0 0	1 XX 00 685 2289 0 25 68 1 1 48 48 48	2 XX 00 701 2193 0 25 79 1 1 48 48 48
3 XX 00 744 1673 0 25 62 1 1 48 48 48	4 XX 00 786 1818 0 25 49 1 1 48 48 48	5 XX 00 752 1869 0 25 33 1 1 48 48 48
6 XX 00 634 1593 0 25 53 1 1 48 48 48	7 XX 00 721 1581 0 25 76 1 1 48 48 48	8 XX 00 682 1630 0 25 74 1 1 48 48 48
9 XX 00 626 2261 0 25 34 1 1 48 48 48	10 XX 00 795 1700 0 25 47 1 1 48 48 48	11 XX 00 740 2222 0 25 47 1 1 48 48 48
12 XX 00 779 1836 0 25 38 1 1 48 48 48	13 XX 00 657 1938 0 25 37 1 1 48 48 48	14 XX 00 687 1961 0 25 58 1 1 48 48 48
15 XX 00 642 1681 0 25 38 1 1 48 48 48	16 XX 00 712 1763 0 25 74 1 1 48 48 48	17 XX 00 776 2184 0 25 51 1 1 48 48 48
18 XX 00 635 1992 0 25 44 1 1 48 48 48	19 XX 00 649 1798 0 25 52 1 1 48 48 48	20 XX 00 765 2120 0 25 79 1 1 48 48 48
21 XX 00 624 2226 0 25 42 1 1 48 48 48	22 XX 00 752 2237 0 25 43 1 1 48 48 48	23 XX 00 657 2167 0 25 57 1 1 48 48 48
24 XX 00 643 1622 0 25 40 1 1 48 48 48	25 XX 00 694 2278 0 25 58 1 1 48 48 48	26 XX 00 774 2299 0 25 59 1 1 48 48 48
27 XX 00 616 1831 0 25 35 1 1 48 48 48	28 XX 00 777 1640 0 25 77 1 1 48 48 48	29 XX 00 766 2148 0 25 77 1 1 48 48 48
30 XX 00 713 2145 0 25 31 1 1 48 48 48	31 XX 00 756 2142 0 25 70 1 1 48 48 48	32 XX 00 777 1834 0 25 79 1 1 48 48 48
33 XX 00 650 1916 0 25 36 1 1 48 48 48	34 XX 00 617 2126 0 25 57 1 1 48 48 48	35 XX 00 683 2250 0 25 54 1 1 48 48 48
36 XX 00 759 2171 0 25 45 1 1 48 48 48	37 XX 00 705 1916 0 25 47 1 1 48 48 48	38 XX 00 791 2221 0 25 71 1 1 48 48 48
39 XX 00 705 1517 0 25 77 1 1 48 48 48	40 XX 00 753 2277 0 25 52 1 1 48 48 48	41 XX 00 752 2138 0 25 78 1 1 48 48 48
42 XX 00 754 2051 0 25 36 1 1 48 48 48	43 XX 00 624 1915 0 25 38 1 1 48 48 48	44 XX 00 726 1514 0 25 51 1 1 48 48 48
45 XX 00 657 2297 0 25 34 1 1 48 48 48	46 XX 00 696 2061 0 25 42 1 1 48 48 48	47 XX 00 738 2288 0 25 76 1 1 48 48 48
48 XX 00 622 1954 0 25 43 1 1 48 48 48	49 XX 00 791 1858 0 25 31 1 1 48 48 48	50 XX 00 718 1824 0 25 38 1 1 48 48 48
51 XX 00 700 1554 0 25 33 1 1 48 48 48	52 XX 00 755 1616 0 25 56 1 1 48 48 48	53 XX 00 647 2079 0 25 36 1 1 48 48 48
54 XX 00 796 2265 0 25 70 1 1 48 48 48	55 XX 00 773 1923 0 25 73 1 1 48 48 48	56 XX 00 755 1762 0 25 33 1 1 48 48 48
57 XX 00 621 2173 0 25 75 1 1 48 48 48	58 XX 00 772 2159 0 25 68 1 1 48 48 48	59 XX 00 735 1998 0 25 32 1 1 48 48 48
60 XX 00 603 1995 0 25 66 1 1 48 48 48	61 XX 00 642 2023 0 25 34 1 1 48 48 48	62 XX 00 712 2089 0 25 48 1 1 48 48 48
63 XX 00 759 2047 0 25 79 1 1 48 48 48	64 XX 00 765 2169 0 25 72 1 1 48 48 48	65 XX 00 651 1973 0 25 36 1 1 48 48 48

Table C.3 (continued)

66 XX 00 715 2237 0 25 67 1 1 48 48 48		67 XX 00 730 1712 0 25 38 1 1 48 48 48		68 XX 00 742 1658 0 25 41 1 1 48 48 48	
69 XX 00 614 1725 0 25 47 1 1 48 48 48		70 XX 00 740 1585 0 25 61 1 1 48 48 48		71 XX 00 739 2026 0 25 36 1 1 48 48 48	
72 XX 00 663 2179 0 25 71 1 1 48 48 48		73 XX 00 675 1651 0 25 71 1 1 48 48 48		74 XX 00 714 1696 0 25 41 1 1 48 48 48	
75 XX 00 785 1632 0 25 51 1 1 48 48 48		76 XX 00 628 1526 0 25 56 1 1 48 48 48		77 XX 00 729 2176 0 25 55 1 1 48 48 48	
78 XX 00 697 1853 0 25 76 1 1 48 48 48		79 XX 00 648 2251 0 25 77 1 1 48 48 48		80 XX 00 634 2009 0 25 40 1 1 48 48 48	
81 XX 00 621 2113 0 25 43 1 1 48 48 48		82 XX 00 767 1534 0 25 51 1 1 48 48 48		83 XX 00 759 2100 0 25 47 1 1 48 48 48	
84 XX 00 788 1755 0 25 70 1 1 48 48 48		85 XX 00 657 2023 0 25 68 1 1 48 48 48		86 XX 00 794 1789 0 25 72 1 1 48 48 48	
87 XX 00 626 1921 0 25 61 1 1 48 48 48		88 XX 00 639 2260 0 25 37 1 1 48 48 48		89 XX 00 622 2283 0 25 71 1 1 48 48 48	
90 XX 00 782 1504 0 25 52 1 1 48 48 48		91 XX 00 648 2297 0 25 76 1 1 48 48 48		92 XX 00 736 1958 0 25 55 1 1 48 48 48	
93 XX 00 605 1923 0 25 67 1 1 48 48 48		94 XX 00 728 1725 0 25 47 1 1 48 48 48		95 XX 00 666 1732 0 25 45 1 1 48 48 48	
96 XX 00 643 1987 0 25 67 1 1 48 48 48		97 XX 00 615 1518 0 25 70 1 1 48 48 48		98 XX 00 688 2008 0 25 44 1 1 48 48 48	
99 XX 00 694 2175 0 25 56 1 1 48 48 48		100 XX 00 714 1925 0 25 72 1 1 48 48 48			
End Supplier					
Begin Location					
101 X Y					
1000 1000	987 1230	821 131	557 1817	495 1246	1438 78
1725 1653	926 276	351 344	1038 491	1243 1886	159 254
1689 814	338 1561	1806 1511	1702 346	1654 43	1528 1286
1347 585	452 6	1732 1163	1309 1710	1551 559	464 158
442 1719	433 53	163 91	1437 1500	1065 1240	1361 1489
1553 104	1903 686	1093 1638	466 274	726 512	59 1578
1086 1379	233 916	951 68	185 1742	1636 1358	1878 57
221 1754	1577 1398	104 1422	1830 776	702 1166	1940 992
1840 1471	518 1979	383 324	175 581	1555 85	894 582
1104 338	501 1234	1548 598	1132 1165	144 1388	838 1610
461 1577	939 782	1571 1427	1405 1923	1264 1627	1921 1627
530 74	460 476	141 1464	1431 1225	657 1110	1124 939
987 1205	347 852	1815 28	218 1580	1173 1788	213 1867
328 75	1066 614	1299 486	182 635	912 1215	1186 879
601 1435	1192 1739	483 1455	814 6	702 1118	1821 165
1029 978	1202 1287	1403 1749	1260 148	1735 504	617 1421
1198 485	1828 1362	1560 340	989 321	195 1405	
End Location					
Begin Param					
Vehicle_height 120		Vehicle_width 96		Far_far_away 10000000	
Vehicle_number 100		Inventory_number 10000		Alpha 10	
Beta 1		Inv_now 10		Max_columns 3000	
Min_distance 1		Weekly 1		Max_iteration 2000	
Max_load 25		Max_id 10000		Min_time 50	
TS_length 977		Max_freq 12		Min_time2 100	
Max_iter2 800					
End Param					

C.4 Problem R6

Table C.4: Problem R6

Begin Route		
1 Capacity Frequency Speed Vehicle		
30 12 1 100		
End Route		
Begin Supplier		
51 Code Docks Start End Break Stop Pallets Round Weight L W H		
90000 00 00 0 3500 0 0 0 1 1 0 0 0	1 XX 00 770 2253 0 25 50 1 1 48 48 48	2 XX 00 629 1963 0 25 53 1 1 48 48 48
3 XX 00 756 1893 0 25 59 1 1 48 48 48	4 XX 00 625 1648 0 25 57 1 1 48 48 48	5 XX 00 667 1504 0 25 57 1 1 48 48 48
6 XX 00 754 2120 0 25 53 1 1 48 48 48	7 XX 00 739 1756 0 25 58 1 1 48 48 48	8 XX 00 719 2042 0 25 53 1 1 48 48 48
9 XX 00 664 1562 0 25 56 1 1 48 48 48	10 XX 00 710 2276 0 25 50 1 1 48 48 48	11 XX 00 624 2208 0 25 54 1 1 48 48 48
12 XX 00 672 1567 0 25 52 1 1 48 48 48	13 XX 00 643 2299 0 25 55 1 1 48 48 48	14 XX 00 750 1824 0 25 57 1 1 48 48 48
15 XX 00 659 2130 0 25 53 1 1 48 48 48	16 XX 00 721 1847 0 25 50 1 1 48 48 48	17 XX 00 674 2046 0 25 57 1 1 48 48 48
18 XX 00 610 1828 0 25 57 1 1 48 48 48	19 XX 00 710 1668 0 25 57 1 1 48 48 48	20 XX 00 780 1995 0 25 59 1 1 48 48 48
21 XX 00 652 2220 0 25 54 1 1 48 48 48	22 XX 00 785 1552 0 25 59 1 1 48 48 48	23 XX 00 697 2058 0 25 52 1 1 48 48 48
24 XX 00 797 2169 0 25 58 1 1 48 48 48	25 XX 00 617 2211 0 25 53 1 1 48 48 48	26 XX 00 701 1952 0 25 56 1 1 48 48 48

Table C.4 (continued)

```
27 XX 00 635 2261 0 25 53 1 1 48 48 48    28 XX 00 665 2174 0 25 56 1 1 48 48 48    29 XX 00 621 2090 0 25 50 1 1 48 48 48
30 XX 00 606 2013 0 25 50 1 1 48 48 48    31 XX 00 792 2157 0 25 54 1 1 48 48 48    32 XX 00 769 1992 0 25 55 1 1 48 48 48
33 XX 00 705 1541 0 25 54 1 1 48 48 48    34 XX 00 746 2195 0 25 54 1 1 48 48 48    35 XX 00 785 1690 0 25 53 1 1 48 48 48
36 XX 00 768 1920 0 25 57 1 1 48 48 48    37 XX 00 668 2164 0 25 54 1 1 48 48 48    38 XX 00 652 1665 0 25 59 1 1 48 48 48
39 XX 00 734 1733 0 25 59 1 1 48 48 48    40 XX 00 699 1972 0 25 52 1 1 48 48 48    41 XX 00 787 1540 0 25 57 1 1 48 48 48
42 XX 00 690 2005 0 25 56 1 1 48 48 48    43 XX 00 689 1645 0 25 54 1 1 48 48 48    44 XX 00 608 2241 0 25 51 1 1 48 48 48
45 XX 00 757 2230 0 25 57 1 1 48 48 48    46 XX 00 717 1643 0 25 53 1 1 48 48 48    47 XX 00 654 1703 0 25 51 1 1 48 48 48
48 XX 00 793 2290 0 25 52 1 1 48 48 48    49 XX 00 625 1681 0 25 52 1 1 48 48 48    50 XX 00 781 1714 0 25 51 1 1 48 48 48
End Supplier
Begin Location
51 X Y
1000 1000    1265 1081    1938 1979    1378 1936    715 1836     1059 1257
1121 437     478 535      1301 1789    507 628      137 1481     1103 772
452 99       635 353      946 1247     1170 1853    559 617      1550 989
1788 1984    73 83        980 1616     92 281       882 700      998 647
1166 173     247 686      1339 191     1467 735     836 1387     1493 1069
209 1632     1797 929     643 137      1279 17      1619 923     145 794
1759 70      828 1200     926 1979     1850 1626    1830 1483    426 226
1827 1141    1739 266     1733 821     1422 1415    1366 1918    1096 947
563 1445     1091 1941    773 215
End Location
Begin Param
Vehicle_height   120      Vehicle_width    96         Far_far_away    10000000
Vehicle_number   100      Inventory_number 10000      Alpha           10
Beta             1        Inv_now          10         Max_columns     3000
Min_distance     1        Weekly           1          Max_iteration   2000
Max_load         25       Max_id           10000      Min_time        50
TS_length        977      Max_freq         12         Min_time2       100
Max_iter2        800
End Param
```

C.5 Problem R8

Table C.5: Problem R8

```
Begin Route
1 Capacity Frequency Speed Vehicle
80 12 1 100
End Route
Begin Supplier
51 Code Docks Start End Break Stop Pallets Round Weight L W H
90000 00 00 0 3500 0 0 0 1 1 0 0 0        1 XX 00 770 2253 0 25 33 1 1 48 48 48     2 XX 00 629 1963 0 25 49 1 1 48 48 48
3 XX 00 756 1893 0 25 76 1 1 48 48 48     4 XX 00 625 1648 0 25 69 1 1 48 48 48     5 XX 00 667 1504 0 25 69 1 1 48 48 48
6 XX 00 754 2120 0 25 45 1 1 48 48 48     7 XX 00 739 1756 0 25 70 1 1 48 48 48     8 XX 00 719 2042 0 25 46 1 1 48 48 48
9 XX 00 664 1562 0 25 63 1 1 48 48 48     10 XX 00 710 2276 0 25 32 1 1 48 48 48    11 XX 00 624 2208 0 25 54 1 1 48 48 48
12 XX 00 672 1567 0 25 41 1 1 48 48 48    13 XX 00 643 2299 0 25 58 1 1 48 48 48    14 XX 00 750 1824 0 25 67 1 1 48 48 48
15 XX 00 659 2130 0 25 47 1 1 48 48 48    16 XX 00 721 1847 0 25 33 1 1 48 48 48    17 XX 00 674 2046 0 25 67 1 1 48 48 48
18 XX 00 610 1828 0 25 68 1 1 48 48 48    19 XX 00 710 1668 0 25 66 1 1 48 48 48    20 XX 00 780 1995 0 25 78 1 1 48 48 48
21 XX 00 652 2220 0 25 54 1 1 48 48 48    22 XX 00 785 1552 0 25 76 1 1 48 48 48    23 XX 00 697 2058 0 25 44 1 1 48 48 48
24 XX 00 797 2169 0 25 71 1 1 48 48 48    25 XX 00 617 2211 0 25 46 1 1 48 48 48    26 XX 00 701 1952 0 25 64 1 1 48 48 48
27 XX 00 635 2261 0 25 45 1 1 48 48 48    28 XX 00 665 2174 0 25 60 1 1 48 48 48    29 XX 00 621 2090 0 25 30 1 1 48 48 48
30 XX 00 606 2013 0 25 34 1 1 48 48 48    31 XX 00 792 2157 0 25 54 1 1 48 48 48    32 XX 00 769 1992 0 25 57 1 1 48 48 48
33 XX 00 705 1541 0 25 51 1 1 48 48 48    34 XX 00 746 2195 0 25 54 1 1 48 48 48    35 XX 00 785 1690 0 25 49 1 1 48 48 48
36 XX 00 768 1920 0 25 66 1 1 48 48 48    37 XX 00 668 2164 0 25 51 1 1 48 48 48    38 XX 00 652 1665 0 25 79 1 1 48 48 48
39 XX 00 734 1733 0 25 77 1 1 48 48 48    40 XX 00 699 1972 0 25 43 1 1 48 48 48    41 XX 00 787 1540 0 25 65 1 1 48 48 48
42 XX 00 690 2005 0 25 62 1 1 48 48 48    43 XX 00 689 1645 0 25 52 1 1 48 48 48    44 XX 00 608 2241 0 25 38 1 1 48 48 48
45 XX 00 757 2230 0 25 68 1 1 48 48 48    46 XX 00 717 1643 0 25 45 1 1 48 48 48    47 XX 00 654 1703 0 25 39 1 1 48 48 48
48 XX 00 793 2290 0 25 41 1 1 48 48 48    49 XX 00 625 1681 0 25 42 1 1 48 48 48    50 XX 00 781 1714 0 25 37 1 1 48 48 48
End Supplier
Begin Location
51 X Y
1000 1000    1265 1081    1938 1979    1378 1936    715 1836     1059 1257
```

Table C.5 (continued)

1121 437	478 535	1301 1789	507 628	137 1481	1103 772
452 99	635 353	946 1247	1170 1853	559 617	1550 989
1788 1984	73 83	980 1616	92 281	882 700	998 647
1166 173	247 686	1339 191	1467 735	836 1387	1493 1069
209 1632	1797 929	643 137	1279 17	1619 923	145 794
1759 70	828 1200	926 1979	1850 1626	1830 1483	426 226
1827 1141	1739 266	1733 821	1422 1415	1366 1918	1096 947
563 1445	1091 1941	773 215			
End Location					
Begin Param					
Vehicle_height 120		Vehicle_width 96		Far_far_away 10000000	
Vehicle_number 100		Inventory_number 10000		Alpha 10	
Beta 1		Inv_now 10		Max_columns 3000	
Min_distance 1		Weekly 1		Max_iteration 2000	
Max_load 25		Max_id 10000		Min_time 50	
TS_length 977		Max_freq 12		Min_time2 100	
Max_iter2 800					
End Param					

C.6 Problem R8-C

Table C.6: Problem R8-C

Begin Route					
1 Capacity Frequency Speed Vehicle					
80 12 1 100					
End Route					
Begin Supplier					
51 Code Docks Start End Break Stop Pallets Round Weight L W H					
90000 00 00 0 3500 0 0 0 1 1 0 0 0		1 XX 00 770 2253 0 25 33 1 1 48 48 48		2 XX 00 629 1963 0 25 49 1 1 48 48 48	
3 XX 00 756 1893 0 25 76 1 1 48 48 48		4 XX 00 625 1648 0 25 69 1 1 48 48 48		5 XX 00 667 1504 0 25 69 1 1 48 48 48	
6 XX 00 754 2120 0 25 45 1 1 48 48 48		7 XX 00 739 1756 0 25 70 1 1 48 48 48		8 XX 00 719 2042 0 25 46 1 1 48 48 48	
9 XX 00 664 1562 0 25 63 1 1 48 48 48		10 XX 00 710 2276 0 25 32 1 1 48 48 48		11 XX 00 624 2208 0 25 54 1 1 48 48 48	
12 XX 00 672 1567 0 25 41 1 1 48 48 48		13 XX 00 643 2299 0 25 58 1 1 48 48 48		14 XX 00 750 1824 0 25 67 1 1 48 48 48	
15 XX 00 659 2130 0 25 47 1 1 48 48 48		16 XX 00 721 1847 0 25 33 1 1 48 48 48		17 XX 00 674 2046 0 25 67 1 1 48 48 48	
18 XX 00 610 1828 0 25 68 1 1 48 48 48		19 XX 00 710 1668 0 25 66 1 1 48 48 48		20 XX 00 780 1995 0 25 78 1 1 48 48 48	
21 XX 00 652 2220 0 25 54 1 1 48 48 48		22 XX 00 785 1552 0 25 76 1 1 48 48 48		23 XX 00 697 2058 0 25 44 1 1 48 48 48	
24 XX 00 797 2169 0 25 71 1 1 48 48 48		25 XX 00 617 2211 0 25 46 1 1 48 48 48		26 XX 00 701 1952 0 25 64 1 1 48 48 48	
27 XX 00 635 2261 0 25 45 1 1 48 48 48		28 XX 00 665 2174 0 25 60 1 1 48 48 48		29 XX 00 621 2090 0 25 30 1 1 48 48 48	
30 XX 00 606 2013 0 25 34 1 1 48 48 48		31 XX 00 792 2157 0 25 54 1 1 48 48 48		32 XX 00 769 1992 0 25 57 1 1 48 48 48	
33 XX 00 705 1541 0 25 51 1 1 48 48 48		34 XX 00 746 2195 0 25 54 1 1 48 48 48		35 XX 00 785 1690 0 25 49 1 1 48 48 48	
36 XX 00 768 1920 0 25 66 1 1 48 48 48		37 XX 00 668 2164 0 25 51 1 1 48 48 48		38 XX 00 652 1665 0 25 79 1 1 48 48 48	
39 XX 00 734 1733 0 25 77 1 1 48 48 48		40 XX 00 699 1972 0 25 43 1 1 48 48 48		41 XX 00 787 1540 0 25 65 1 1 48 48 48	
42 XX 00 690 2005 0 25 62 1 1 48 48 48		43 XX 00 689 1645 0 25 52 1 1 48 48 48		44 XX 00 608 2241 0 25 38 1 1 48 48 48	
45 XX 00 757 2230 0 25 68 1 1 48 48 48		46 XX 00 717 1643 0 25 45 1 1 48 48 48		47 XX 00 654 1703 0 25 39 1 1 48 48 48	
48 XX 00 793 2290 0 25 41 1 1 48 48 48		49 XX 00 625 1681 0 25 42 1 1 48 48 48		50 XX 00 781 1714 0 25 37 1 1 48 48 48	
End Supplier					
Begin Location					
51 X Y					
1000 1000	1265 1081	1938 1979	1378 1936	715 164	1059 1257
879 437	478 535	1301 1789	507 628	1137 1481	1103 1772
452 99	635 353	1946 1247	1170 1853	559 617	450 989
1788 1984	73 83	1980 1616	92 281	882 700	998 647
166 173	247 686	1339 1191	1467 1735	836 387	1493 1069
209 368	1797 1929	643 137	1279 1017	1619 1077	145 794
241 70	828 800	1926 1979	1850 1626	1830 1483	426 226
1827 1141	1739 1266	267 821	1422 1415	1366 1918	904 947
1563 1445	1091 1941	773 215			
End Location					
Begin Param					
Vehicle_height 120		Vehicle_width 96		Far_far_away 10000000	
Vehicle_number 100		Inventory_number 10000		Alpha 10	

Table C.6 (continued)

Beta 1	Inv_now 10	Max_columns 3000
Min_distance 1	Weekly 1	Max_iteration 2000
Max_load 25	Max_id 10000	Min_time 50
TS_length 977	Max_freq 12	Min_time2 100
Max_iter2 800		
End Param		

C.7 Problem R11

Table C.7: Problem R11

Begin Route					
1 Capacity Frequency Speed Vehicle					
55 12 1 100					
End Route					
Begin Supplier					
51 Code Docks Start End Break Stop Pallets Round Weight L W H					
90000 00 00 0 3500 0 0 0 1 1 0 0 0		1 XX 00 770 2253 0 25 50 1 1 48 48 48		2 XX 00 629 1963 0 25 53 1 1 48 48 48	
3 XX 00 756 1893 0 25 59 1 1 48 48 48		4 XX 00 625 1648 0 25 57 1 1 48 48 48		5 XX 00 667 1504 0 25 57 1 1 48 48 48	
6 XX 00 754 2120 0 25 53 1 1 48 48 48		7 XX 00 739 1756 0 25 58 1 1 48 48 48		8 XX 00 719 2042 0 25 53 1 1 48 48 48	
9 XX 00 664 1562 0 25 56 1 1 48 48 48		10 XX 00 710 2276 0 25 50 1 1 48 48 48		11 XX 00 624 2208 0 25 54 1 1 48 48 48	
12 XX 00 672 1567 0 25 52 1 1 48 48 48		13 XX 00 643 2299 0 25 55 1 1 48 48 48		14 XX 00 750 1824 0 25 57 1 1 48 48 48	
15 XX 00 659 2130 0 25 53 1 1 48 48 48		16 XX 00 721 1847 0 25 50 1 1 48 48 48		17 XX 00 674 2046 0 25 57 1 1 48 48 48	
18 XX 00 610 1828 0 25 57 1 1 48 48 48		19 XX 00 710 1668 0 25 57 1 1 48 48 48		20 XX 00 780 1995 0 25 59 1 1 48 48 48	
21 XX 00 652 2220 0 25 54 1 1 48 48 48		22 XX 00 785 1552 0 25 59 1 1 48 48 48		23 XX 00 697 2058 0 25 52 1 1 48 48 48	
24 XX 00 797 2169 0 25 58 1 1 48 48 48		25 XX 00 617 2211 0 25 53 1 1 48 48 48		26 XX 00 701 1952 0 25 56 1 1 48 48 48	
27 XX 00 635 2261 0 25 53 1 1 48 48 48		28 XX 00 665 2174 0 25 56 1 1 48 48 48		29 XX 00 621 2090 0 25 50 1 1 48 48 48	
30 XX 00 606 2013 0 25 50 1 1 48 48 48		31 XX 00 792 2157 0 25 54 1 1 48 48 48		32 XX 00 769 1992 0 25 55 1 1 48 48 48	
33 XX 00 705 1541 0 25 54 1 1 48 48 48		34 XX 00 746 2195 0 25 54 1 1 48 48 48		35 XX 00 785 1690 0 25 53 1 1 48 48 48	
36 XX 00 768 1920 0 25 57 1 1 48 48 48		37 XX 00 668 2164 0 25 54 1 1 48 48 48		38 XX 00 652 1665 0 25 59 1 1 48 48 48	
39 XX 00 734 1733 0 25 59 1 1 48 48 48		40 XX 00 699 1972 0 25 52 1 1 48 48 48		41 XX 00 787 1540 0 25 57 1 1 48 48 48	
42 XX 00 690 2005 0 25 56 1 1 48 48 48		43 XX 00 689 1645 0 25 54 1 1 48 48 48		44 XX 00 608 2241 0 25 51 1 1 48 48 48	
45 XX 00 757 2230 0 25 57 1 1 48 48 48		46 XX 00 717 1643 0 25 53 1 1 48 48 48		47 XX 00 654 1703 0 25 51 1 1 48 48 48	
48 XX 00 793 2290 0 25 52 1 1 48 48 48		49 XX 00 625 1681 0 25 52 1 1 48 48 48		50 XX 00 781 1714 0 25 51 1 1 48 48 48	
End Supplier					
Begin Location					
51 X Y					
1000 1000	1265 1081	1938 1979	1378 1936	715 1836	1059 1257
1121 437	478 535	1301 1789	507 628	137 1481	1103 772
452 99	635 353	946 1247	1170 1853	559 617	1550 989
1788 1984	73 83	980 1616	92 281	882 700	998 647
1166 173	247 686	1339 191	1467 735	836 1387	1493 1069
209 1632	1797 929	643 137	1279 17	1619 923	145 794
1759 70	828 1200	926 1979	1850 1626	1830 1483	426 226
1827 1141	1739 266	1733 821	1422 1415	1366 1918	1096 947
563 1445	1091 1941	773 215			
End Location					
Begin Param					
Vehicle_height 120		Vehicle_width 96		Far_far_away 10000000	
Vehicle_number 100		Inventory_number 10000		Alpha 10	
Beta 1		Inv_now 10		Max_columns 3000	
Min_distance 1		Weekly 1		Max_iteration 2000	
Max_load 25		Max_id 10000		Min_time 50	
TS_length 977		Max_freq 12		Min_time2 100	
Max_iter2 800					
End Param					

Appendix D: Simulation results

This appendix contains the results of the simulation models in Chapter 4.

```
                            ARENA Simulation Results
                        Summary for Replication 1 of 5

Project:JSS Simulation                           Run execution date : 6/20/2003
Analyst:Keng Chuah                               Model revision date: 6/20/2003

Replication ended at time      : 192000.0
Statistics were cleared at time: 20000.0
Statistics accumulated for time: 172000.0

                                 TALLY VARIABLES

Identifier                Average   Half Width  Minimum    Maximum   Observations
_________________________________________________________________________________

Route Process.TotalTim  400.00     .00000     400.00     400.00        431
Supplier Process Load.  49.987     .01734     49.375     50.517        430
Supplier Process Dock.  49.999     .01496     49.486     50.608        430
Consumption Process.To  49.993     .00763     49.359     50.709       3396
Plant Process Dock.VAT  199.99     .02132     199.42     200.61        430
Route Process.VATimePe  400.00     .00000     400.00     400.00        431
Production Process.VAT  49.677     1.5875     .03276     594.42       3375
Production Process.Tot  758.54     (Corr)     1.1912     2074.1       3375
Production Process.Wai  708.86     (Corr)     .00000     1945.4       3375
Supplier Process Load.  49.987     .01734     49.375     50.517        430
Plant Process Docking.  .00000     .00000     .00000     .00000        430
Consumption Process.VA  49.993     .00763     49.359     50.709       3396
Plant Process Dock.Tot  199.99     .02132     199.42     200.61        430
Plant Process Load.VAT  50.000     .00000     50.000     50.000        430
Supplier Process Dock.  49.999     .01496     49.486     50.608        430
Plant Process Docking.  199.99     .02500     199.34     200.54        430
Plant Process Docking.  199.99     .02500     199.34     200.54        430
Plant Process Load.Tot  50.000     .00000     50.000     50.000        430
PALLETS.VATime              --         --         --         --          0
PALLETS.NVATime             --         --         --         --          0
PALLETS.WaitTime            --         --         --         --          0
PALLETS.TranTime            --         --         --         --          0
PALLETS.OtherTime           --         --         --         --          0
PALLETS.TotalTime           --         --         --         --          0
PARTS.VATime            257.64     (Corr)     49.359     832.63       6792
PARTS.NVATime           .00000     .00000     .00000     .00000       6792
PARTS.WaitTime          28529.     (Corr)     .00000     97198.       6792
PARTS.TranTime          700.00     5.2769E-14 .00000     1400.0       6792
PARTS.OtherTime         .00000     .00000     .00000     .00000       6792
PARTS.TotalTime         4582.8     (Corr)     49.550     8427.3       6792
TRAILER.VATime              --         --         --         --          0
TRAILER.NVATime             --         --         --         --          0
TRAILER.WaitTime            --         --         --         --          0
TRAILER.TranTime            --         --         --         --          0
TRAILER.OtherTime           --         --         --         --          0
TRAILER.TotalTime           --         --         --         --          0
KANBAN.VATime               --         --         --         --          0
KANBAN.NVATime              --         --         --         --          0
KANBAN.WaitTime             --         --         --         --          0
KANBAN.TranTime             --         --         --         --          0
KANBAN.OtherTime            --         --         --         --          0
KANBAN.TotalTime            --         --         --         --          0
CYCLE.VATime                --         --         --         --          0
CYCLE.NVATime               --         --         --         --          0
CYCLE.WaitTime              --         --         --         --          0
CYCLE.TranTime              --         --         --         --          0
CYCLE.OtherTime             --         --         --         --          0
CYCLE.TotalTime             --         --         --         --          0
Consumption Hold Suppl  2093.8     27.667     1820.5     2719.8       3396
Production Hold Order.  43256.     (Corr)     20150.     47130.       3400
```

Production Process.Que	709.20	(Corr)	.00000	1945.4	3375
Supplier Hold Kanban.Q	330.00	.64078	49.486	400.79	4255
Production Batch.Queue	73.545	3.6642	.00000	656.51	3376
Kanban Hold Transport.	313.42	(Corr)	19.569	650.97	853
Consumption Hold Palle	416.41	(Corr)	20.311	1252.6	811
Supplier Hold Pickup.Q	49.987	.02084	49.375	50.517	851
Consumption Hold Part.	--	--	--	--	0
Plant Hold Kanban.Queu	50.000	.00000	50.000	50.000	851
Production Hold Transp	2599.2	(Corr)	1297.0	3654.3	851
Consumption Seize.Queu	2064.6	(Corr)	.00000	4626.1	3396
Plant Hold Trailer.Que	650.01	.03461	648.90	651.15	431
Plant Request.Queue.Wa	.00000	.00000	.00000	.00000	430
Kanban Hold Order.Queu	1003.8	(Corr)	420.38	1853.3	850
Plant Process Docking.	.00000	.00000	.00000	.00000	430

DISCRETE-CHANGE VARIABLES

Identifier	Average	Half Width	Minimum	Maximum	Final Value
Supply Level for Consu	41.356	(Corr)	36.000	43.000	43.000
PALLETS.WIP	.00000	(Insuf)	.00000	.00000	.00000
PARTS.WIP	1104.7	(Corr)	1056.0	1164.0	1108.0
TRAILER.WIP	10.000	(Insuf)	10.000	10.000	10.000
KANBAN.WIP	31.000	(Insuf)	31.000	31.000	31.000
CYCLE.WIP	1.0000	(Insuf)	1.0000	1.0000	1.0000
PRODUCTION RESOURCE.Nu	.97486	.01819	.00000	1.0000	1.0000
PRODUCTION RESOURCE.Nu	1.0000	(Insuf)	1.0000	1.0000	1.0000
PRODUCTION RESOURCE.Ut	.97486	.01819	.00000	1.0000	1.0000
CONSUMPTION RESOURCE.N	.98696	.01230	.00000	1.0000	1.0000
CONSUMPTION RESOURCE.N	1.0000	(Insuf)	1.0000	1.0000	1.0000
CONSUMPTION RESOURCE.U	.98696	.01230	.00000	1.0000	1.0000
PLANT RESOURCE.NumberB	.50000	(Corr)	.00000	1.0000	1.0000
PLANT RESOURCE.NumberS	1.0000	(Insuf)	1.0000	1.0000	1.0000
PLANT RESOURCE.Utiliza	.50000	(Corr)	.00000	1.0000	1.0000
Consumption Hold Suppl	41.356	(Corr)	36.000	43.000	43.000
Production Hold Order.	884.99	(Corr)	859.00	900.00	868.00
Production Process.Que	14.030	(Corr)	.00000	40.000	31.000
Supplier Hold Kanban.Q	8.1636	.07895	.00000	10.000	8.0000
Production Batch.Queue	1.4435	.06298	.00000	4.0000	.00000
Kanban Hold Transport.	1.5441	(Corr)	.00000	4.0000	1.0000
Consumption Hold Palle	1.9649	(Corr)	.00000	7.0000	1.0000
Supplier Hold Pickup.Q	.24732	.00320	.00000	2.0000	.00000
Consumption Hold Part.	.00000	(Insuf)	.00000	.00000	.00000
Plant Hold Kanban.Queu	.24738	.00325	.00000	2.0000	2.0000
Production Hold Transp	12.769	(Corr)	6.0000	19.000	9.0000
Consumption Seize.Queu	41.497	(Corr)	.00000	93.000	64.000
Plant Hold Trailer.Que	1.6250	(Corr)	1.0000	2.0000	1.0000
Plant Request.Queue.Nu	.00000	(Insuf)	.00000	.00000	.00000
Kanban Hold Order.Queu	4.9649	(Corr)	3.0000	10.000	4.0000
Plant Process Docking.	.00000	(Insuf)	.00000	.00000	.00000

OUTPUTS

Identifier	Value
Plant Process Docking	430.00
Production Process Num	3375.0
Supplier Process Dock	430.00
Supplier Process Dock	21499.
Plant Process Load Num	431.00
Production Process Acc	1.6766E+05
Production Process Num	3400.0
Plant Process Load Acc	21500.
Route Process Number O	431.00
Production Process Acc	2.3924E+06
Plant Process Docking	430.00
Supplier Process Load	430.00
Route Process Accum VA	1.7240E+05
Supplier Process Dock	430.00

Consumption Process Nu	3396.0
Plant Process Docking	.00000
Plant Process Dock Num	430.00
Plant Process Load Num	430.00
Supplier Process Load	21494.
Plant Process Dock Num	430.00
Supplier Process Load	430.00
Consumption Process Ac	1.6978E+05
Consumption Process Nu	3396.0
Route Process Number I	431.00
Plant Process Docking	85999.
Plant Process Dock Acc	85998.
PALLETS.NumberIn	.00000
PALLETS.NumberOut	.00000
PARTS.NumberIn	7668.0
PARTS.NumberOut	7642.0
TRAILER.NumberIn	.00000
TRAILER.NumberOut	.00000
KANBAN.NumberIn	.00000
KANBAN.NumberOut	.00000
CYCLE.NumberIn	.00000
CYCLE.NumberOut	.00000
PRODUCTION RESOURCE.Ti	3375.0
PRODUCTION RESOURCE.Sc	.97486
CONSUMPTION RESOURCE.T	3396.0
CONSUMPTION RESOURCE.S	.98696
PLANT RESOURCE.TimesUs	430.00
PLANT RESOURCE.Schedul	.50000
System.NumberOut	6792.0

Beginning replication 2 of 5

Project:JSS Simulation Run execution date : 6/20/2003
Analyst:Keng Chuah Model revision date: 6/20/2003

Replication ended at time : 192000.0
Statistics were cleared at time: 20000.0
Statistics accumulated for time: 172000.0

TALLY VARIABLES

Identifier	Average	Half Width	Minimum	Maximum	Observations
Route Process.TotalTim	400.00	.00000	400.00	400.00	431
Supplier Process Load.	50.015	.01881	49.240	50.779	430
Supplier Process Dock.	49.996	.02089	49.428	50.480	430
Consumption Process.To	50.003	.00809	49.314	50.681	3440
Plant Process Dock.VAT	200.00	.01285	199.51	200.52	430
Route Process.VATimePe	400.00	.00000	400.00	400.00	431
Production Process.VAT	50.201	1.5063	.00932	388.66	3388
Production Process.Tot	1049.4	(Corr)	2.6042	3796.8	3388
Production Process.Wai	999.21	(Corr)	.00000	3727.9	3388
Supplier Process Load.	50.015	.01881	49.240	50.779	430
Plant Process Docking.	.00000	.00000	.00000	.00000	430
Consumption Process.VA	50.003	.00809	49.314	50.681	3440
Plant Process Dock.Tot	200.00	.01285	199.51	200.52	430
Plant Process Load.VAT	50.000	.00000	50.000	50.000	430
Supplier Process Dock.	49.996	.02089	49.428	50.480	430
Plant Process Docking.	199.99	.01846	199.46	200.61	430
Plant Process Docking.	199.99	.01846	199.46	200.61	430
Plant Process Load.Tot	50.000	.00000	50.000	50.000	430
PALLETS.VATime	--	--	--	--	0
PALLETS.NVATime	--	--	--	--	0
PALLETS.WaitTime	--	--	--	--	0
PALLETS.TranTime	--	--	--	--	0
PALLETS.OtherTime	--	--	--	--	0
PALLETS.TotalTime	--	--	--	--	0
PARTS.VATime	258.06	(Corr)	49.314	737.85	6880
PARTS.NVATime	.00000	.00000	.00000	.00000	6880
PARTS.WaitTime	28626.	(Corr)	1619.8	96054.	6880

PARTS.TranTime	700.00	3.7874E-14	.00000	1400.0	6880
PARTS.OtherTime	.00000	.00000	.00000	.00000	6880
PARTS.TotalTime	4717.6	(Corr)	1670.1	7462.3	6880
TRAILER.VATime	--	--	--	--	0
TRAILER.NVATime	--	--	--	--	0
TRAILER.WaitTime	--	--	--	--	0
TRAILER.TranTime	--	--	--	--	0
TRAILER.OtherTime	--	--	--	--	0
TRAILER.TotalTime	--	--	--	--	0
KANBAN.VATime	--	--	--	--	0
KANBAN.NVATime	--	--	--	--	0
KANBAN.WaitTime	--	--	--	--	0
KANBAN.TranTime	--	--	--	--	0
KANBAN.OtherTime	--	--	--	--	0
KANBAN.TotalTime	--	--	--	--	0
CYCLE.VATime	--	--	--	--	0
CYCLE.NVATime	--	--	--	--	0
CYCLE.WaitTime	--	--	--	--	0
CYCLE.TranTime	--	--	--	--	0
CYCLE.OtherTime	--	--	--	--	0
CYCLE.TotalTime	--	--	--	--	0
Consumption Hold Suppl	1900.7	(Corr)	1533.1	2088.2	3440
Production Hold Order.	42620.	(Corr)	20150.	45174.	3436
Production Process.Que	999.92	(Corr)	.00000	3727.9	3388
Supplier Hold Kanban.Q	329.99	.80264	49.428	400.74	4300
Production Batch.Queue	76.339	(Corr)	.00000	505.47	3388
Kanban Hold Transport.	647.66	.04049	249.45	651.43	862
Consumption Hold Palle	--	--	--	--	0
Supplier Hold Pickup.Q	50.015	.01881	49.240	50.779	860
Consumption Hold Part.	--	--	--	--	0
Plant Hold Kanban.Queu	50.000	.00000	50.000	50.000	860
Production Hold Transp	2647.5	(Corr)	191.48	3684.1	859
Consumption Seize.Queu	2853.9	(Corr)	1619.8	4159.2	3440
Plant Hold Trailer.Que	649.98	.04049	648.56	651.43	431
Plant Request.Queue.Wa	.00000	.00000	.00000	.00000	430
Kanban Hold Order.Queu	602.56	(Corr)	398.31	802.45	859
Plant Process Docking.	.00000	.00000	.00000	.00000	430

DISCRETE-CHANGE VARIABLES

Identifier	Average	Half Width	Minimum	Maximum	Final Value
Supply Level for Consu	37.972	(Corr)	30.000	42.000	33.000
PALLETS.WIP	.00000	(Insuf)	.00000	.00000	.00000
PARTS.WIP	1109.6	(Corr)	1052.0	1153.0	1063.0
TRAILER.WIP	10.000	(Insuf)	10.000	10.000	10.000
KANBAN.WIP	31.000	(Insuf)	31.000	31.000	31.000
CYCLE.WIP	1.0000	(Insuf)	1.0000	1.0000	1.0000
PRODUCTION RESOURCE.Nu	.98871	(Corr)	.00000	1.0000	1.0000
PRODUCTION RESOURCE.Nu	1.0000	(Insuf)	1.0000	1.0000	1.0000
PRODUCTION RESOURCE.Ut	.98871	(Corr)	.00000	1.0000	1.0000
CONSUMPTION RESOURCE.N	1.0000	.00000	.00000	1.0000	1.0000
CONSUMPTION RESOURCE.N	1.0000	(Insuf)	1.0000	1.0000	1.0000
CONSUMPTION RESOURCE.U	1.0000	.00000	.00000	1.0000	1.0000
PLANT RESOURCE.NumberB	.50000	(Corr)	.00000	1.0000	1.0000
PLANT RESOURCE.NumberS	1.0000	(Insuf)	1.0000	1.0000	1.0000
PLANT RESOURCE.Utiliza	.50000	(Corr)	.00000	1.0000	1.0000
Consumption Hold Suppl	37.972	(Corr)	30.000	42.000	33.000
Production Hold Order.	878.82	(Corr)	825.00	900.00	842.00
Production Process.Que	20.189	(Corr)	.00000	74.000	57.000
Supplier Hold Kanban.Q	8.2499	(Corr)	.00000	10.000	8.0000
Production Batch.Queue	1.5034	(Corr)	.00000	4.0000	2.0000
Kanban Hold Transport.	3.2368	(Corr)	1.0000	4.0000	1.0000
Consumption Hold Palle	.00000	(Insuf)	.00000	.00000	.00000
Supplier Hold Pickup.Q	.25008	(Corr)	.00000	2.0000	.00000
Consumption Hold Part.	.00000	(Insuf)	.00000	.00000	.00000
Plant Hold Kanban.Queu	.25000	(Corr)	.00000	2.0000	2.0000
Production Hold Transp	13.090	(Corr)	.00000	19.000	3.0000
Consumption Seize.Queu	57.489	(Corr)	32.000	84.000	62.000
Plant Hold Trailer.Que	1.6249	(Corr)	1.0000	2.0000	1.0000

Plant Request.Queue.Nu	.00000	(Insuf)	.00000	.00000	.00000
Kanban Hold Order.Queu	3.0130	.00000	3.0000	5.0000	4.0000
Plant Process Docking.	.00000	(Insuf)	.00000	.00000	.00000

OUTPUTS

Identifier	Value
Plant Process Docking	430.00
Production Process Num	3388.0
Supplier Process Dock	430.00
Supplier Process Dock	21498.
Plant Process Load Num	431.00
Production Process Acc	1.7008E+05
Production Process Num	3436.0
Plant Process Load Acc	21500.
Route Process Number O	431.00
Production Process Acc	3.3853E+06
Plant Process Docking	430.00
Supplier Process Load	430.00
Route Process Accum VA	1.7240E+05
Supplier Process Dock	430.00
Consumption Process Nu	3440.0
Plant Process Docking	.00000
Plant Process Dock Num	430.00
Plant Process Load Num	430.00
Supplier Process Load	21506.
Plant Process Dock Num	430.00
Supplier Process Load	430.00
Consumption Process Ac	1.7201E+05
Consumption Process Nu	3440.0
Route Process Number I	431.00
Plant Process Docking	85999.
Plant Process Dock Acc	86001.
PALLETS.NumberIn	.00000
PALLETS.NumberOut	.00000
PARTS.NumberIn	7696.0
PARTS.NumberOut	7739.0
TRAILER.NumberIn	.00000
TRAILER.NumberOut	.00000
KANBAN.NumberIn	.00000
KANBAN.NumberOut	.00000
CYCLE.NumberIn	.00000
CYCLE.NumberOut	.00000
PRODUCTION RESOURCE.Ti	3388.0
PRODUCTION RESOURCE.Sc	.98871
CONSUMPTION RESOURCE.T	3440.0
CONSUMPTION RESOURCE.S	1.0000
PLANT RESOURCE.TimesUs	430.00
PLANT RESOURCE.Schedul	.50000
System.NumberOut	6880.0

Beginning replication 3 of 5

Project:JSS Simulation   Run execution date : 6/20/2003
Analyst:Keng Chuah   Model revision date: 6/20/2003

Replication ended at time   : 192000.0
Statistics were cleared at time: 20000.0
Statistics accumulated for time: 172000.0

TALLY VARIABLES

Identifier	Average	Half Width	Minimum	Maximum	Observations
Route Process.TotalTim	400.00	.00000	400.00	400.00	431
Supplier Process Load.	49.994	.01313	49.412	50.564	430
Supplier Process Dock.	49.984	(Corr)	49.224	50.634	430
Consumption Process.To	49.994	.00514	49.156	50.836	3375

Plant Process Dock.VAT	200.01	(Corr)	199.42	200.58	430
Route Process.VATimePe	400.00	.00000	400.00	400.00	431
Production Process.VAT	48.941	1.3684	.00382	492.36	3428
Production Process.Tot	1012.9	(Corr)	.45076	3167.7	3428
Production Process.Wai	964.01	(Corr)	.00000	3122.4	3428
Supplier Process Load.	49.994	.01313	49.412	50.564	430
Plant Process Docking.	.00000	.00000	.00000	.00000	430
Consumption Process.VA	49.994	.00514	49.156	50.836	3375
Plant Process Dock.Tot	200.01	(Corr)	199.42	200.58	430
Plant Process Load.VAT	50.000	.00000	50.000	50.000	430
Supplier Process Dock.	49.984	(Corr)	49.224	50.634	430
Plant Process Docking.	199.99	.01807	199.32	200.59	430
Plant Process Docking.	199.99	.01807	199.32	200.59	430
Plant Process Load.Tot	50.000	.00000	50.000	50.000	430
PALLETS.VATime	--	--	--	--	0
PALLETS.NVATime	--	--	--	--	0
PALLETS.WaitTime	--	--	--	--	0
PALLETS.TranTime	--	--	--	--	0
PALLETS.OtherTime	--	--	--	--	0
PALLETS.TotalTime	--	--	--	--	0
PARTS.VATime	257.80	(Corr)	49.156	727.84	6750
PARTS.NVATime	.00000	.00000	.00000	.00000	6750
PARTS.WaitTime	27173.	(Corr)	.00000	98547.	6750
PARTS.TranTime	700.00	2.0540E-14	.00000	1400.0	6750
PARTS.OtherTime	.00000	.00000	.00000	.00000	6750
PARTS.TotalTime	3572.3	(Corr)	49.537	8952.4	6750
TRAILER.VATime	--	--	--	--	0
TRAILER.NVATime	--	--	--	--	0
TRAILER.WaitTime	--	--	--	--	0
TRAILER.TranTime	--	--	--	--	0
TRAILER.OtherTime	--	--	--	--	0
TRAILER.TotalTime	--	--	--	--	0
KANBAN.VATime	--	--	--	--	0
KANBAN.NVATime	--	--	--	--	0
KANBAN.WaitTime	--	--	--	--	0
KANBAN.TranTime	--	--	--	--	0
KANBAN.OtherTime	--	--	--	--	0
KANBAN.TotalTime	--	--	--	--	0
CYCLE.VATime	--	--	--	--	0
CYCLE.NVATime	--	--	--	--	0
CYCLE.WaitTime	--	--	--	--	0
CYCLE.TranTime	--	--	--	--	0
CYCLE.OtherTime	--	--	--	--	0
CYCLE.TotalTime	--	--	--	--	0
Consumption Hold Suppl	1875.0	(Corr)	1567.9	3133.3	3375
Production Hold Order.	42443.	(Corr)	20150.	47553.	3384
Production Process.Que	963.37	(Corr)	.00000	3122.4	3428
Supplier Hold Kanban.Q	329.99	.90795	49.224	400.99	4245
Production Batch.Queue	71.857	3.4701	.00000	565.95	3428
Kanban Hold Transport.	555.97	(Corr)	6.8736	651.02	850
Consumption Hold Palle	674.57	(Insuf)	70.079	1698.8	211
Supplier Hold Pickup.Q	49.994	.01303	49.412	50.564	849
Consumption Hold Part.	--	--	--	--	0
Plant Hold Kanban.Queu	50.000	.00000	50.000	50.000	848
Production Hold Transp	2561.2	(Corr)	581.85	3689.1	849
Consumption Seize.Queu	605.75	(Corr)	.00000	2015.2	3375
Plant Hold Trailer.Que	650.01	.03989	648.79	651.15	431
Plant Request.Queue.Wa	.00000	.00000	.00000	.00000	430
Kanban Hold Order.Queu	774.39	(Corr)	398.48	2358.3	846
Plant Process Docking.	.00000	.00000	.00000	.00000	430

DISCRETE-CHANGE VARIABLES

Identifier	Average	Half Width	Minimum	Maximum	Final Value
Supply Level for Consu	36.884	(Corr)	31.000	43.000	43.000
PALLETS.WIP	.00000	(Insuf)	.00000	.00000	.00000
PARTS.WIP	1064.5	(Corr)	1012.0	1099.0	1086.0
TRAILER.WIP	10.000	(Insuf)	10.000	10.000	10.000
KANBAN.WIP	31.000	(Insuf)	31.000	31.000	31.000

CYCLE.WIP	1.0000	(Insuf)	1.0000	1.0000	1.0000
PRODUCTION RESOURCE.Nu	.97524	.01316	.00000	1.0000	1.0000
PRODUCTION RESOURCE.Nu	1.0000	(Insuf)	1.0000	1.0000	1.0000
PRODUCTION RESOURCE.Ut	.97524	.01316	.00000	1.0000	1.0000
CONSUMPTION RESOURCE.N	.98108	(Corr)	.00000	1.0000	1.0000
CONSUMPTION RESOURCE.N	1.0000	(Insuf)	1.0000	1.0000	1.0000
CONSUMPTION RESOURCE.U	.98108	(Corr)	.00000	1.0000	1.0000
PLANT RESOURCE.NumberB	.49998	(Corr)	.00000	1.0000	1.0000
PLANT RESOURCE.NumberS	1.0000	(Insuf)	1.0000	1.0000	1.0000
PLANT RESOURCE.Utiliza	.49998	(Corr)	.00000	1.0000	1.0000
Consumption Hold Suppl	36.884	(Corr)	31.000	43.000	43.000
Production Hold Order.	880.14	(Corr)	836.00	900.00	897.00
Production Process.Que	18.878	(Corr)	.00000	63.000	2.0000
Supplier Hold Kanban.Q	8.1444	.07907	.00000	10.000	8.0000
Production Batch.Queue	1.4319	.05366	.00000	4.0000	1.0000
Kanban Hold Transport.	2.7370	(Corr)	.00000	4.0000	.00000
Consumption Hold Palle	.83654	(Corr)	.00000	9.0000	3.0000
Supplier Hold Pickup.Q	.24677	(Corr)	.00000	2.0000	.00000
Consumption Hold Part.	.00000	(Insuf)	.00000	.00000	.00000
Plant Hold Kanban.Queu	.24651	.00412	.00000	2.0000	2.0000
Production Hold Transp	12.710	(Corr)	2.0000	19.000	14.000
Consumption Seize.Queu	11.882	(Corr)	.00000	41.000	6.0000
Plant Hold Trailer.Que	1.6250	(Corr)	1.0000	2.0000	1.0000
Plant Request.Queue.Nu	.00000	(Insuf)	.00000	.00000	.00000
Kanban Hold Order.Queu	3.8365	(Corr)	3.0000	12.000	6.0000
Plant Process Docking.	.00000	(Insuf)	.00000	.00000	.00000

OUTPUTS

Identifier	Value
Plant Process Docking	430.00
Production Process Num	3428.0
Supplier Process Dock	430.00
Supplier Process Dock	21493.
Plant Process Load Num	431.00
Production Process Acc	1.6777E+05
Production Process Num	3384.0
Plant Process Load Acc	21500.
Route Process Number O	431.00
Production Process Acc	3.3046E+06
Plant Process Docking	430.00
Supplier Process Load	430.00
Route Process Accum VA	1.7240E+05
Supplier Process Dock	430.00
Consumption Process Nu	3375.0
Plant Process Docking	.00000
Plant Process Dock Num	430.00
Plant Process Load Num	430.00
Supplier Process Load	21497.
Plant Process Dock Num	430.00
Supplier Process Load	430.00
Consumption Process Ac	1.6873E+05
Consumption Process Nu	3375.0
Route Process Number I	431.00
Plant Process Docking	85997.
Plant Process Dock Acc	86005.
PALLETS.NumberIn	.00000
PALLETS.NumberOut	.00000
PARTS.NumberIn	7660.0
PARTS.NumberOut	7596.0
TRAILER.NumberIn	.00000
TRAILER.NumberOut	.00000
KANBAN.NumberIn	.00000
KANBAN.NumberOut	.00000
CYCLE.NumberIn	.00000
CYCLE.NumberOut	.00000
PRODUCTION RESOURCE.Ti	3428.0
PRODUCTION RESOURCE.Sc	.97524
CONSUMPTION RESOURCE.T	3375.0

CONSUMPTION RESOURCE.S	.98108
PLANT RESOURCE.TimesUs	430.00
PLANT RESOURCE.Schedul	.49998
System.NumberOut	6750.0

Beginning replication 4 of 5

Project:JSS Simulation   Run execution date : 6/20/2003
Analyst:Keng Chuah   Model revision date: 6/20/2003

Replication ended at time   : 192000.0
Statistics were cleared at time: 20000.0
Statistics accumulated for time: 172000.0

TALLY VARIABLES

Identifier	Average	Half Width	Minimum	Maximum	Observations
Route Process.TotalTim	400.00	.00000	400.00	400.00	431
Supplier Process Load.	50.013	.01952	49.464	50.587	430
Supplier Process Dock.	49.989	.01865	49.439	50.530	430
Consumption Process.To	49.996	.00750	49.317	50.718	3345
Plant Process Dock.VAT	199.99	.01819	199.49	200.58	430
Route Process.VATimePe	400.00	.00000	400.00	400.00	431
Production Process.VAT	48.596	1.8181	.01376	372.00	3382
Production Process.Tot	557.80	(Corr)	1.3188	1868.3	3382
Production Process.Wai	509.21	(Corr)	.00000	1753.1	3382
Supplier Process Load.	50.013	.01952	49.464	50.587	430
Plant Process Docking.	.00000	.00000	.00000	.00000	430
Consumption Process.VA	49.996	.00750	49.317	50.718	3345
Plant Process Dock.Tot	199.99	.01819	199.49	200.58	430
Plant Process Load.VAT	50.000	.00000	50.000	50.000	430
Supplier Process Dock.	49.989	.01865	49.439	50.530	430
Plant Process Docking.	199.99	.01714	199.41	200.55	430
Plant Process Docking.	199.99	.01714	199.41	200.55	430
Plant Process Load.Tot	50.000	.00000	50.000	50.000	430
PALLETS.VATime	--	--	--	--	0
PALLETS.NVATime	--	--	--	--	0
PALLETS.WaitTime	--	--	--	--	0
PALLETS.TranTime	--	--	--	--	0
PALLETS.OtherTime	--	--	--	--	0
PALLETS.TotalTime	--	--	--	--	0
PARTS.VATime	257.25	(Corr)	49.317	758.34	6690
PARTS.NVATime	.00000	.00000	.00000	.00000	6690
PARTS.WaitTime	27696.	(Corr)	.00000	97354.	6690
PARTS.TranTime	700.00	4.1081E-14	.00000	1400.0	6690
PARTS.OtherTime	.00000	.00000	.00000	.00000	6690
PARTS.TotalTime	3835.6	(Corr)	49.536	9272.0	6690
TRAILER.VATime	--	--	--	--	0
TRAILER.NVATime	--	--	--	--	0
TRAILER.WaitTime	--	--	--	--	0
TRAILER.TranTime	--	--	--	--	0
TRAILER.OtherTime	--	--	--	--	0
TRAILER.TotalTime	--	--	--	--	0
KANBAN.VATime	--	--	--	--	0
KANBAN.NVATime	--	--	--	--	0
KANBAN.WaitTime	--	--	--	--	0
KANBAN.TranTime	--	--	--	--	0
KANBAN.OtherTime	--	--	--	--	0
KANBAN.TotalTime	--	--	--	--	0
CYCLE.VATime	--	--	--	--	0
CYCLE.NVATime	--	--	--	--	0
CYCLE.WaitTime	--	--	--	--	0
CYCLE.TranTime	--	--	--	--	0
CYCLE.OtherTime	--	--	--	--	0
CYCLE.TotalTime	--	--	--	--	0
Consumption Hold Suppl	1817.8	(Corr)	778.75	2881.0	3345
Production Hold Order.	43584.	(Corr)	20150.	47656.	3368
Production Process.Que	509.03	(Corr)	.00000	1753.1	3382
Supplier Hold Kanban.Q	329.99	(Corr)	49.439	400.71	4220

Production Batch.Queue	72.748	2.8965	.00000	484.54	3380
Kanban Hold Transport.	345.70	(Corr)	5.7344	651.17	846
Consumption Hold Palle	593.23	(Corr)	23.590	1752.9	585
Supplier Hold Pickup.Q	50.012	.01860	49.464	50.587	844
Consumption Hold Part.	--	--	--	--	0
Plant Hold Kanban.Queu	50.000	.00000	50.000	50.000	844
Production Hold Transp	2815.4	(Corr)	1323.1	3677.6	844
Consumption Seize.Queu	646.79	(Corr)	.00000	2113.5	3345
Plant Hold Trailer.Que	650.00	.04011	648.96	651.17	431
Plant Request.Queue.Wa	.00000	.00000	.00000	.00000	430
Kanban Hold Order.Queu	1023.5	(Corr)	398.50	2552.4	842
Plant Process Docking.	.00000	.00000	.00000	.00000	430

DISCRETE-CHANGE VARIABLES

Identifier	Average	Half Width	Minimum	Maximum	Final Value
Supply Level for Consu	35.551	(Corr)	15.000	43.000	41.000
PALLETS.WIP	.00000	(Insuf)	.00000	.00000	.00000
PARTS.WIP	1075.0	(Corr)	1034.0	1122.0	1078.0
TRAILER.WIP	10.000	(Insuf)	10.000	10.000	10.000
KANBAN.WIP	31.000	(Insuf)	31.000	31.000	31.000
CYCLE.WIP	1.0000	(Insuf)	1.0000	1.0000	1.0000
PRODUCTION RESOURCE.Nu	.95499	.02437	.00000	1.0000	1.0000
PRODUCTION RESOURCE.Nu	1.0000	(Insuf)	1.0000	1.0000	1.0000
PRODUCTION RESOURCE.Ut	.95499	.02437	.00000	1.0000	1.0000
CONSUMPTION RESOURCE.N	.97241	(Corr)	.00000	1.0000	1.0000
CONSUMPTION RESOURCE.N	1.0000	(Insuf)	1.0000	1.0000	1.0000
CONSUMPTION RESOURCE.U	.97241	(Corr)	.00000	1.0000	1.0000
PLANT RESOURCE.NumberB	.49998	(Corr)	.00000	1.0000	1.0000
PLANT RESOURCE.NumberS	1.0000	(Insuf)	1.0000	1.0000	1.0000
PLANT RESOURCE.Utiliza	.49998	(Corr)	.00000	1.0000	1.0000
Consumption Hold Suppl	35.551	(Corr)	15.000	43.000	41.000
Production Hold Order.	889.08	(Corr)	863.00	900.00	895.00
Production Process.Que	9.9580	(Corr)	.00000	36.000	4.0000
Supplier Hold Kanban.Q	8.0964	.15983	.00000	10.000	8.0000
Production Batch.Queue	1.4297	.05715	.00000	4.0000	3.0000
Kanban Hold Transport.	1.6899	(Corr)	.00000	4.0000	.00000
Consumption Hold Palle	2.0206	(Corr)	.00000	8.0000	2.0000
Supplier Hold Pickup.Q	.24541	.00549	.00000	2.0000	.00000
Consumption Hold Part.	.00000	(Insuf)	.00000	.00000	.00000
Plant Hold Kanban.Queu	.24535	.00546	.00000	2.0000	2.0000
Production Hold Transp	13.815	(Corr)	6.0000	19.000	14.000
Consumption Seize.Queu	12.568	(Corr)	.00000	43.000	3.0000
Plant Hold Trailer.Que	1.6250	(Corr)	1.0000	2.0000	1.0000
Plant Request.Queue.Nu	.00000	(Insuf)	.00000	.00000	.00000
Kanban Hold Order.Queu	5.0206	(Corr)	3.0000	11.000	5.0000
Plant Process Docking.	.00000	(Insuf)	.00000	.00000	.00000

OUTPUTS

Identifier	Value
Plant Process Docking	430.00
Production Process Num	3382.0
Supplier Process Dock	430.00
Supplier Process Dock	21495.
Plant Process Load Num	431.00
Production Process Acc	1.6435E+05
Production Process Num	3368.0
Plant Process Load Acc	21500.
Route Process Number O	431.00
Production Process Acc	1.7222E+06
Plant Process Docking	430.00
Supplier Process Load	430.00
Route Process Accum VA	1.7240E+05
Supplier Process Dock	430.00
Consumption Process Nu	3345.0
Plant Process Docking	.00000

Plant Process Dock Num	430.00
Plant Process Load Num	430.00
Supplier Process Load	21505.
Plant Process Dock Num	430.00
Supplier Process Load	430.00
Consumption Process Ac	1.6724E+05
Consumption Process Nu	3345.0
Route Process Number I	431.00
Plant Process Docking	85997.
Plant Process Dock Acc	85999.
PALLETS.NumberIn	.00000
PALLETS.NumberOut	.00000
PARTS.NumberIn	7565.0
PARTS.NumberOut	7532.0
TRAILER.NumberIn	.00000
TRAILER.NumberOut	.00000
KANBAN.NumberIn	.00000
KANBAN.NumberOut	.00000
CYCLE.NumberIn	.00000
CYCLE.NumberOut	.00000
PRODUCTION RESOURCE.Ti	3382.0
PRODUCTION RESOURCE.Sc	.95499
CONSUMPTION RESOURCE.T	3345.0
CONSUMPTION RESOURCE.S	.97241
PLANT RESOURCE.TimesUs	430.00
PLANT RESOURCE.Schedul	.49998
System.NumberOut	6690.0

Beginning replication 5 of 5

Project:JSS Simulation Run execution date : 6/20/2003
Analyst:Keng Chuah Model revision date: 6/20/2003

Replication ended at time : 192000.0
Statistics were cleared at time: 20000.0
Statistics accumulated for time: 172000.0

TALLY VARIABLES

Identifier	Average	Half Width	Minimum	Maximum	Observations
Route Process.TotalTim	400.00	.00000	400.00	400.00	431
Supplier Process Load.	49.997	.01743	49.416	50.569	430
Supplier Process Dock.	49.999	.01510	49.515	50.508	430
Consumption Process.To	49.996	.00690	49.211	50.812	3397
Plant Process Dock.VAT	199.99	.02319	199.32	200.49	430
Route Process.VATimePe	400.00	.00000	400.00	400.00	431
Production Process.VAT	50.782	2.2691	.02786	383.82	3360
Production Process.Tot	1672.4	(Corr)	6.3602	4307.9	3360
Production Process.Wai	1621.6	(Corr)	.00000	4255.5	3360
Supplier Process Load.	49.997	.01743	49.416	50.569	430
Plant Process Docking.	.00000	.00000	.00000	.00000	430
Consumption Process.VA	49.996	.00690	49.211	50.812	3397
Plant Process Dock.Tot	199.99	.02319	199.32	200.49	430
Plant Process Load.VAT	50.000	.00000	50.000	50.000	430
Supplier Process Dock.	49.999	.01510	49.515	50.508	430
Plant Process Docking.	199.99	.01757	199.35	200.55	430
Plant Process Docking.	199.99	.01757	199.35	200.55	430
Plant Process Load.Tot	50.000	.00000	50.000	50.000	430
PALLETS.VATime	--	--	--	--	0
PALLETS.NVATime	--	--	--	--	0
PALLETS.WaitTime	--	--	--	--	0
PALLETS.TranTime	--	--	--	--	0
PALLETS.OtherTime	--	--	--	--	0
PALLETS.TotalTime	--	--	--	--	0
PARTS.VATime	258.43	(Corr)	49.211	749.61	6794
PARTS.NVATime	.00000	.00000	.00000	.00000	6794
PARTS.WaitTime	27708.	(Corr)	.00000	96715.	6794
PARTS.TranTime	700.00	.00000	.00000	1400.0	6794
PARTS.OtherTime	.00000	.00000	.00000	.00000	6794

PARTS.TotalTime	3759.0	(Corr)	49.668	8287.8	6794
TRAILER.VATime	--	--	--	--	0
TRAILER.NVATime	--	--	--	--	0
TRAILER.WaitTime	--	--	--	--	0
TRAILER.TranTime	--	--	--	--	0
TRAILER.OtherTime	--	--	--	--	0
TRAILER.TotalTime	--	--	--	--	0
KANBAN.VATime	--	--	--	--	0
KANBAN.NVATime	--	--	--	--	0
KANBAN.WaitTime	--	--	--	--	0
KANBAN.TranTime	--	--	--	--	0
KANBAN.OtherTime	--	--	--	--	0
KANBAN.TotalTime	--	--	--	--	0
CYCLE.VATime	--	--	--	--	0
CYCLE.NVATime	--	--	--	--	0
CYCLE.WaitTime	--	--	--	--	0
CYCLE.TranTime	--	--	--	--	0
CYCLE.OtherTime	--	--	--	--	0
CYCLE.TotalTime	--	--	--	--	0
Consumption Hold Suppl	1875.6	(Corr)	.00000	2430.7	3397
Production Hold Order.	42648.	(Corr)	20018.	46404.	3360
Production Process.Que	1621.6	(Corr)	.00000	4255.5	3360
Supplier Hold Kanban.Q	329.91	.49206	49.515	400.75	4195
Production Batch.Queue	77.314	3.5287	.00000	510.84	3360
Kanban Hold Transport.	225.93	(Corr)	3.8518	388.33	842
Consumption Hold Palle	467.13	(Corr)	79.667	1022.0	708
Supplier Hold Pickup.Q	49.998	.01733	49.416	50.569	839
Consumption Hold Part.	73.765	(Insuf)	.05601	200.08	18
Plant Hold Kanban.Queu	50.000	.00000	50.000	50.000	840
Production Hold Transp	1748.2	(Corr)	8.9555	3552.9	834
Consumption Seize.Queu	1502.0	(Corr)	.00000	4889.1	3397
Plant Hold Trailer.Que	650.00	.03688	649.02	651.03	431
Plant Request.Queue.Wa	.00000	.00000	.00000	.00000	430
Kanban Hold Order.Queu	1173.2	(Corr)	861.49	2001.3	840
Plant Process Docking.	.00000	.00000	.00000	.00000	430

DISCRETE-CHANGE VARIABLES

Identifier	Average	Half Width	Minimum	Maximum	Final Value
Supply Level for Consu	36.791	(Corr)	.00000	43.000	3.0000
PALLETS.WIP	.00000	(Insuf)	.00000	.00000	.00000
PARTS.WIP	1067.2	(Corr)	1015.0	1118.0	1107.0
TRAILER.WIP	10.000	(Insuf)	10.000	10.000	10.000
KANBAN.WIP	31.000	(Insuf)	31.000	31.000	31.000
CYCLE.WIP	1.0000	(Insuf)	1.0000	1.0000	1.0000
PRODUCTION RESOURCE.Nu	.99254	.01230	.00000	1.0000	1.0000
PRODUCTION RESOURCE.Nu	1.0000	(Insuf)	1.0000	1.0000	1.0000
PRODUCTION RESOURCE.Ut	.99254	.01230	.00000	1.0000	1.0000
CONSUMPTION RESOURCE.N	.99525	.00571	.00000	1.0000	1.0000
CONSUMPTION RESOURCE.N	1.0000	(Insuf)	1.0000	1.0000	1.0000
CONSUMPTION RESOURCE.U	.99525	.00571	.00000	1.0000	1.0000
PLANT RESOURCE.NumberB	.49999	(Corr)	.00000	1.0000	1.0000
PLANT RESOURCE.NumberS	1.0000	(Insuf)	1.0000	1.0000	1.0000
PLANT RESOURCE.Utiliza	.49999	(Corr)	.00000	1.0000	1.0000
Consumption Hold Suppl	36.791	(Corr)	.00000	43.000	3.0000
Production Hold Order.	867.33	(Corr)	821.00	900.00	883.00
Production Process.Que	31.675	(Corr)	.00000	78.000	16.000
Supplier Hold Kanban.Q	8.0470	(Corr)	.00000	10.000	7.0000
Production Batch.Queue	1.5125	.05257	.00000	4.0000	3.0000
Kanban Hold Transport.	1.1027	(Corr)	.00000	2.0000	.00000
Consumption Hold Palle	1.9124	(Corr)	.00000	6.0000	.00000
Supplier Hold Pickup.Q	.24389	.00484	.00000	2.0000	.00000
Consumption Hold Part.	.00772	(Insuf)	.00000	1.0000	.00000
Plant Hold Kanban.Queu	.24419	.00535	.00000	2.0000	2.0000
Production Hold Transp	8.5656	(Corr)	.00000	18.000	15.000
Consumption Seize.Queu	30.719	(Corr)	.00000	92.000	85.000
Plant Hold Trailer.Que	1.6250	(Corr)	1.0000	2.0000	1.0000
Plant Request.Queue.Nu	.00000	(Insuf)	.00000	.00000	.00000
Kanban Hold Order.Queu	5.7382	(Corr)	4.0000	9.0000	8.0000

Plant Process Docking.	.00000	(Insuf)	.00000	.00000	.00000

OUTPUTS

Identifier	Value
Plant Process Docking	430.00
Production Process Num	3360.0
Supplier Process Dock	430.00
Supplier Process Dock	21499.
Plant Process Load Num	431.00
Production Process Acc	1.7063E+05
Production Process Num	3360.0
Plant Process Load Acc	21500.
Route Process Number O	431.00
Production Process Acc	5.4488E+06
Plant Process Docking	430.00
Supplier Process Load	430.00
Route Process Accum VA	1.7240E+05
Supplier Process Dock	430.00
Consumption Process Nu	3397.0
Plant Process Docking	.00000
Plant Process Dock Num	430.00
Plant Process Load Num	430.00
Supplier Process Load	21498.
Plant Process Dock Num	430.00
Supplier Process Load	430.00
Consumption Process Ac	1.6984E+05
Consumption Process Nu	3397.0
Route Process Number I	431.00
Plant Process Docking	85999.
Plant Process Dock Acc	85997.
PALLETS.NumberIn	.00000
PALLETS.NumberOut	.00000
PARTS.NumberIn	7673.0
PARTS.NumberOut	7634.0
TRAILER.NumberIn	.00000
TRAILER.NumberOut	.00000
KANBAN.NumberIn	.00000
KANBAN.NumberOut	.00000
CYCLE.NumberIn	.00000
CYCLE.NumberOut	.00000
PRODUCTION RESOURCE.Ti	3360.0
PRODUCTION RESOURCE.Sc	.99254
CONSUMPTION RESOURCE.T	3397.0
CONSUMPTION RESOURCE.S	.99525
PLANT RESOURCE.TimesUs	430.00
PLANT RESOURCE.Schedul	.49999
System.NumberOut	6794.0

Output Summary for 5 Replications

Project:JSS Simulation Run execution date : 6/20/2003
Analyst:Keng Chuah Model revision date: 6/20/2003

OUTPUTS

Identifier	Average	Half-width	Minimum	Maximum	# Replications
Plant Process Docking	430.00	.00000	430.00	430.00	5
Production Process Num	3386.6	31.524	3360.0	3428.0	5
Supplier Process Dock	430.00	.00000	430.00	430.00	5
Supplier Process Dock	21497.	3.5410	21493.	21499.	5
Plant Process Load Num	431.00	.00000	431.00	431.00	5
Production Process Acc	1.6810E+05	3082.4	1.6435E+05	1.7063E+05	5
Production Process Num	3389.6	37.425	3360.0	3436.0	5
Plant Process Load Acc	21500.	.00000	21500.	21500.	5
Route Process Number O	431.00	.00000	431.00	431.00	5

```
Production Process Acc 3.2507E+06 1.7475E+06 1.7222E+06 5.4488E+06 5
Plant Process Docking  430.00     .00000     430.00     430.00     5
Supplier Process Load  430.00     .00000     430.00     430.00     5
Route Process Accum VA 1.7240E+05 .00000     1.7240E+05 1.7240E+05 5
Supplier Process Dock  430.00     .00000     430.00     430.00     5
Consumption Process Nu 3390.6     43.154     3345.0     3440.0     5
Plant Process Docking  .00000     .00000     .00000     .00000     5
Plant Process Dock Num 430.00     .00000     430.00     430.00     5
Plant Process Load Num 430.00     .00000     430.00     430.00     5
Supplier Process Load  21500.     6.4986     21494.     21506.     5
Plant Process Dock Num 430.00     .00000     430.00     430.00     5
Supplier Process Load  430.00     .00000     430.00     430.00     5
Consumption Process Ac 1.6952E+05 2167.9     1.6724E+05 1.7201E+05 5
Consumption Process Nu 3390.6     43.154     3345.0     3440.0     5
Route Process Number I 431.00     .00000     431.00     431.00     5
Plant Process Docking  85998.     1.2219     85997.     85999.     5
Plant Process Dock Acc 86000.     3.9167     85997.     86005.     5
PALLETS.NumberIn       .00000     .00000     .00000     .00000     5
PALLETS.NumberOut      .00000     .00000     .00000     .00000     5
PARTS.NumberIn         7652.4     62.890     7565.0     7696.0     5
PARTS.NumberOut        7628.6     93.710     7532.0     7739.0     5
TRAILER.NumberIn       .00000     .00000     .00000     .00000     5
TRAILER.NumberOut      .00000     .00000     .00000     .00000     5
KANBAN.NumberIn        .00000     .00000     .00000     .00000     5
KANBAN.NumberOut       .00000     .00000     .00000     .00000     5
CYCLE.NumberIn         .00000     .00000     .00000     .00000     5
CYCLE.NumberOut        .00000     .00000     .00000     .00000     5
PRODUCTION RESOURCE.Ti 3386.6     31.524     3360.0     3428.0     5
PRODUCTION RESOURCE.Sc .97727     .01831     .95499     .99254     5
CONSUMPTION RESOURCE.T 3390.6     43.154     3345.0     3440.0     5
CONSUMPTION RESOURCE.S .98714     .01367     .97241     1.0000     5
PLANT RESOURCE.TimesUs 430.00     .00000     430.00     430.00     5
PLANT RESOURCE.Schedul .49999     7.6055E-06 .49998     .50000     5
System.NumberOut       6781.2     86.308     6690.0     6880.0     5

Simulation run time: 0.27 minutes.
Simulation run complete.
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Vita

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2. Chuah, K. H. and J. C. Yingling, "Routing for a Just-in-time Supply Pickup and Delivery System" in review for *Transportation Science*, in press.